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ASD-TDR-62-506

COMPARISON OF HIGH ENERGY RATE (DYNAPAK) AND CONVENTIONAL EXTRUSION OF REFRACTORY METALS

TECHNICAL DOCUMENTARY REPORT NR ASD-TDR-62-506

September 1962

Directorate of Materials and Processes
Aeronautical Systems Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

Project No. 7381, Task No. 73811

(Prepared under Contract Nr AF 33(616)-7842 by the Westinghouse Electric Corporation, Blairsville, Pennsylvania; Dirk G. Rabenold, author.)

FOREWORD

This report was prepared by the Materials Manufacturing Division of Westinghouse Electric Corporation under USAF Contract No. AF 33(616)-7842. This contract was initiated under Project No. 7381, Task No. 73811. The work was administered under the direction of the Directorate of Materials and Processes, Deputy Commander/Technology, Aeronautical Systems Division, with Lt. C. M. Pierce acting as project engineer.

This report covers work conducted from March 1961 to March 1962.

This work was conducted at the Materials Manufacturing Division of Westinghouse, Blairsville, Pennsylvania, and at the American Brake Shoe Company Research Laboratories, Mahwah, New Jersey. Significant contributions were made to the project by Mr. D. H. Moreno of Westinghouse, and by technical personnel of the American Brake Shoe Company.

ABSTRACT

A comparison was made of the surface quality, dimensions, chemistry, hardness, tensile properties, and recrystallization behavior of extrusions produced on a Model 1810 Dynapak high-velocity machine and on a 700-ton Loewy high speed extrusion press. Three temperatures were established which represented hot work, cold work, and a combination of hot and cold work, by making preliminary extrusions on the Dynapak machine. Arc cast billets, with a nominal diameter of three inches, of two refractory alloys, a Mo-25W-0.1Zr alloy and a W-0.6Cb alloy, were then extruded at a constant 4:1 reduction ratio from the same three temperatures on both machines. The results of this work indicate that equally good surfaces can be obtained from either process when proper lubrication and die preparation techniques are used; a lower hot working temperature can be used for high-velocity extrusions; and, a lower recrystallization temperature is obtained in material cold worked on the Dynapak. The latter fact indicates that high-velocity-extruded metals retain a higher degree of internal stress than conventionally-extruded metals.

This technical documentary report has been reviewed and is approved.

I. [redacted], Chief
Physical Metallurgy Branch
Metals and Ceramics Laboratory
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INTRODUCTION

The state-of-the-art of extruding metals has advanced in recent years to the point where high strength molybdenum alloys can be successfully extruded into round bars and shapes. Very recently, tungsten alloys also have been extruded with some success. The introduction of high energy rate machines in the past few years has made available a new tool for both forging and extrusion work. Because of the extremely rapid working accomplished by these machines, it appeared that several advantages could be obtained by using them for extruding refractory metals.

1. The short working time would prevent excessive die wear by decreasing the contact time between refractory metals and the tooling at high temperatures.

2. Higher temperatures would be allowed because of this short contact time.

3. The combination of rapid working and allowable high temperatures would produce more favorable conditions for converting the coarse dendritic structure of arc-cast billets to a completely recrystallized structure.

The purpose of this contract was to compare the quality, dimensions, metallurgical characteristics, and physical properties of highly refractory materials when extruded by the high energy rate (Dynapak) and the conventional extrusion process. This comparison would then allow a more knowledgeable decision regarding which process would effect the best combination of material characteristics for a particular application. For this comparison, three-inch diameter arc-cast billets (billets for the high-velocity process were actually machined to a diameter of 2-7/8 inches) of a Mo-25W-0.1Zr alloy and a W-0.6Cb alloy were chosen to be extruded by the two processes from three temperatures. These two alloys were chosen because for these alloys there presently exists conventional extrusion experience and high temperature tensile test data which would assist in the comparison. The three temperatures were to produce, respectively, 100% hot work, 100% cold work, and approximately equal amounts of hot and cold work. Furthermore, the three temperatures were to be established by examining high-velocity extrusions and then the same three temperatures used for each process.

At the beginning of this contract, it was planned to make the high-velocity extrusions on a Model 1210 Dynapak machine. It soon became apparent, however, that the 150,000 ft. lbs. of energy of the machine could not extrude a sufficient volume of a three-inch diameter billet to be evaluated. As a result, negotiations were concluded with the American Brake Shoe Company to use their larger Model 1810 Dynapak machine which delivers an impact energy of 430,000 ft. lbs.

A unique feature of this investigation was the fact that a constant fairly small reduction ratio of 4:1 was maintained for all the extrusions regardless of

Manuscript released by author June 1962 for publication as an ASD Technical Documentary Report

the process or the temperature used. This permitted a better evaluation of the effect of temperatures and extrusion rates on the recrystallization behavior of the as-cast structure and the uniformity of work in the extruded structure.

EXPERIMENTAL PROCEDURE

1. General

The general procedure laid out for this contract was to extrude by high-velocity methods a sufficient number of billets to establish three temperatures that would produce 100% hot work, 100% cold work, and an intermediate structure. Two as-cast billets would then be extruded at each of these temperatures on each of two machines: a Dynapak machine and a conventional extrusion press.

Molybdenum Alloy

A total of nineteen extrusions were made for this phase of the contract. Seven base-information extrusions were made by high-velocity techniques, one of which was subsequently used for a program extrusion. Five program extrusions were made on the Dynapak and seven program extrusions were made on a conventional extrusion press. One of the latter was made merely to establish the operating characteristics of the extrusion press and instruments.

Tungsten Alloy

A total of nineteen extrusions were made for this phase of the contract. Six billets were used for the base-information work on the high-velocity machine. No base-information press extrusions were made, but the information from the molybdenum press extrusions was used to assist in this work. Six Dynapak extrusions and seven press extrusions were then made for the comparison. The extra press extrusion was made to replace one which required a long transfer time from furnace to press.

2. Billet Preparation

Molybdenum Alloy

The billets for this part of the contract were obtained from eight vacuum-arc-cast ingots melted at the Westinghouse Materials Manufacturing Division, Blairsville, Pennsylvania. The electrode material was purchased from the General Electric Company as preblended and sintered bars measuring approximately two inches in diameter by 24 to 27 inches in length. Each bar had a 1/8-inch diameter cored hole in the center extending the full length of the bar. Each end of each bar was drilled and tapped to provide a female thread 3/4 inches x NC x 1-1/8 inches deep. Three bars were then joined by a stud to form a finished electrode 80 to 84 inches long.

Zirconium was added by inserting the proper amount of 0.076-inch diameter zirconium wire through the cored hole and extending 3/8 inches beyond one end. The electrodes were melted into 3-1/2-inch diameter copper molds with approximately

3500 amperes and 28 volts. Melting time was 21 minutes for an ingot 22 inches long.

After the hot top and bottom sections of each ingot were removed, a 1/8-inch slice was cut from the top and bottom ends and sampled for chemical analysis. Each ingot was then machined to 3.00 inches in diameter and ultrasonically tested. Further sectioning of the ingots is indicated in Figure 1. In some cases, four three-inch lengths were obtained. Those ingots used to provide high-velocity extrusion billets were further machined to 2.875 inches in diameter. The 5-1/2 inch length shown in the sketch was used for a different program. A 120° chamfer was machined on each billet 1/4 inch back from the top end. Hardness readings were taken on the top and bottom ends of each billet. Finally, a glass lubricant was sprayed onto the surface of the material to a depth of 0.010 to 0.015 inch.

The dimensions, chemistry and hardness of the as-cast ingots are presented in Table 1. Chemical analyses were made at the Materials Manufacturing Division. An indication of the homogeneity of the as-cast ingots can be seen in Figure 2 which shows four typical transverse macrographs and one longitudinal section. It also shows the typical microstructure of the as-cast material.

Tungsten Alloy

The billets for this portion of the contract were purchased from the Refractomet Division of the Universal Cyclops Steel Corporation. Each ingot was machined at Universal Cyclops to 3.00 inches in diameter and was ultrasonically tested.

A 120° chamfer, 1/4-inch back from the top end, was also machined on each billet at Universal Cyclops. Hardness readings were taken on the top and the bottom end at the edge and mid-radius positions. Finally, a glass lubricant was sprayed onto the surface of the material to a depth of 0.010 to 0.015 inch on the radius.

The dimensions, chemistry, and hardness of the as-cast ingots are presented in Table 2. The analyses shown are those reported by Universal Cyclops. The homogeneity of the as-cast ingot structure can be seen in Figure 3 which shows typical longitudinal microstructure (100X) and transverse macrostructure (1X) of the as-cast tungsten-columbium alloy ingot.

3. Machines and Tools

The same equipment was used for both the molybdenum alloy extrusions and the tungsten alloy extrusions. The two machines used for this work (Figures 4 and 5) were a 700-ton Loewy high speed press and a Model 1810 Dynapak machine manufactured by the Convair Division of the General Dynamics Corporation. The Loewy press can deliver an effective constant force of 600 tons at a speed of 14 inches per second, which is higher than other conventional presses. In contrast the Model 1810 Dynapak machine delivers a maximum impact energy of 430,000 foot-pounds at an initial speed of approximately 900 inches per second. No special tooling was used on the conventional press and the tooling used on the high-velocity machine was similar in design to that described by Reimann[1]. The diameter of the container on the press was 3-1/8 inches and that used for the high-velocity machine was 3 inches.

All dies were made from H13 tool steel and were provided with a 120° entrance angle. The dies for both the high-velocity and conventional extrusions of the tungsten alloy were coated with a 0.020- to 0.025-inch thick layer of zirconia by the plasma flame spray technique. The coating was underlayed with a 0.003- to 0.005-inch thick layer of a nickel-chromium alloy. Uncoated dies were used for all the molybdenum extrusions.

4. Heating Procedures

All billets were heated in specially constructed induction heating furnaces. The furnace used at the American Brake Shoe facilities can be seen in Figure 5 and was similar in design to the one used at the Westinghouse facility. The furnace consists of a brass chamber, approximately 12 by 12 by 18 inches, which is water cooled by copper tubing brazed to the outside. Sight ports are provided at the top and side to observe the billet and to obtain optical temperature readings. Inert gas is admitted to the chamber through copper tubing at the bottom of the furnace and, if desired, at the sight ports. The gas outlet is at the top of the chamber. Billets are supported on molybdenum pins which are placed into holes in a water cooled copper plate at the bottom of the chamber. This copper plate contains an "O"-ring seal and is attached to an air cylinder which raises or lowers the plate.

The induction coil for the high-velocity billets was made by winding copper tubing into a coil 5 inches I.D. by 6 inches long. The power supply was a 300 KW generator operating at 960 cycles. Suitable capacitors were available to balance the load. The induction coil for the press extrusion billets was made by winding copper tubing into a coil 3-1/2 inches I.D. by 8 inches long. This power supply was a 100 KW generator operating at 3000 cycles. Again, suitable capacitors were available to balance the load. The water-cooled power leads to the coil entered the back of the furnace chamber and were insulated from the chamber by Micarta blocks. Both coils were coated on the inside with a thin layer of refractory cement.

The temperature of the billets was raised fairly slowly: first to approximately 1200 - 1500°F, where it was held for several minutes, then to 2200 - 2500°F, and again held several minutes. Finally, the temperature was raised to the desired level and held for a minimum of three minutes. Invariably, the desired temperature was exceeded during this time and the proper adjustments were made to achieve correct billet conditions.

All temperature measurements except for those on the first base-information high-velocity billet of molybdenum alloy, which were made with an optical pyrometer, were made with a tungsten - 100% rhenium thermocouple. This thermocouple was placed into a 3/16-inch diameter, 3/8-inch deep hole in the billet, at approximately the mid-radius position.

Two thermocouples were used to measure temperature on each billet. Temperature measurements were made with a Leeds & Northrup millivolt potentiometer and a millivolt vs temperature chart supplied by the thermocouple manufacturer, Minneapolis Honeywell Regulator Company.

The time required to transfer the billets from the heating furnace to either the high-velocity machine or the press was recorded and is given in Tables No. 3, 4, 5 and 6. This transfer time is the elapsed time from the moment the furnace was shut off to the moment the extrusion process started. The relative position of the furnace and machine is shown in Figures 4 and 5 for the extrusion press and high-velocity machine, respectively.

5. Extrusion Parameters

The extrusion parameters used for the base-information high-velocity extrusion of the molybdenum alloy and the tungsten alloy are shown on Tables 3 and 5, respectively. Note that these extrusions were made from approximately 3-inch long billets in the molybdenum alloy and approximately 4-inch long billets in the tungsten alloy. The extrusion parameters for the program extrusions (for both extrusion processes) are shown in Tables 3, 4, 5 and 6 for molybdenum and tungsten, respectively. Both the high-velocity and press program extrusions were made from approximately 4-inch long billets.

The only parameter that was substantially varied during the program was the extrusion temperature. The other parameters such as die condition, die steel, and lubrication are merely listed for completeness and were not evaluated for their effect on either process.

6. Sampling and Evaluation Techniques

The sampling technique used for both the molybdenum alloy and the tungsten alloy for the program press extrusions and high-velocity extrusions is shown in Figure 6. The difference in technique was necessary because of the shortness of the high-velocity extrusions. A slight variation was made for the tungsten extrusions in that slices "A" and "B" were reversed. This was done to obtain a micrographic sample sufficiently far from the nose to obtain worked material. All samples for micrographic examination were obtained by cutting the indicated slices into quarters. One quarter was then examined on the longitudinal face from the center to the surface of the extrusion. Oxygen and nitrogen samples were obtained by cutting two 1/4-inch squares from the center of the indicated 1/8-inch thick slices and were analyzed by the vacuum extraction method. Transverse hardness readings were taken on the "D" slice after grinding the faces smooth and flat. This slice was then quartered to provide one of the micrographs above, a microhardness sample, which was mounted and polished for DPH readings, and two quarters for recrystallization samples. Four more recrystallization samples were obtained by quartering the "E" slices. For the molybdenum alloy, these six samples were vacuum annealed for one hour at 2500°F, 2600°F, 2700°F, 2800°F, 2900°F, or 3000°F. For the tungsten alloy, five recrystallization samples were vacuum annealed for one hour at 2700°F, 2850°F, 3000°F, 3150°F, or 3300°F. All the recrystallization samples were subsequently examined for changes in microstructure.

Tensile specimens were obtained by making a longitudinal cut through the section indicated. For the molybdenum alloy, all six of the press extrusions thus provided four tensile specimens each. Only two high-velocity extrusions, however, were long enough to provide enough material for four tensile specimens. Tensile specimens used for room temperature tests were machined into standard 0.357-inch

diameter specimens with threaded ends. Tensile specimens used for 2000°F tests were machined into special button head specimens with a 0.357-inch diameter gauge section 1-5/8 inches long. Half of the tensile specimens were tested in the as-extruded condition at room temperature and at 2000°F. The remaining specimens were heat treated at 3000°F for one hour. This temperature was chosen because results of the work described below indicated that 3000°F would recrystallize the cold worked high-velocity extrusions. Two tensile specimens were obtained from an as-cast billet. One was tested at room temperature and the other at 2000°F.

For the tungsten alloy, all seven press extrusions provided four tensile specimens each. All high-velocity extrusions provided only two tensile specimens. Tensile test specimens used for room temperature tests were machined into special button head specimens with a 0.357-inch diameter gauge section 1-1/2 inches long. Tensile specimens used for 3000°F were also machined into special button head specimens with a 0.235-inch diameter gauge section 1-1/2 inches long. Half of the tensile test specimens were tested in the as-extruded condition at room temperature and at 3000°F. The remaining tensile test specimens were heat treated (vacuum annealed) at 3000°F for one hour. This temperature was chosen because the results of the work described below indicated that 3000°F would recrystallize the cold worked high-velocity extrusions. All elevated temperature tensile tests were run at the Performance Laboratory of the Westinghouse Central Technical Service Department and the testing equipment is amply described by Vandergrift.[2]

All the program extrusions were photographed in the as-extruded condition and visually examined for surface quality.

PHASE I MOLYBDENUM ALLOY EXTRUSIONS

RESULTS

Base Information Extrusions

Since the major purpose of this part of the investigation was to establish three temperatures which would produce, respectively, 100% hot work, 100% cold work, and a structure approximately 50% recrystallized, the evaluation of these base-information extrusions was limited to surface quality, dimensions, and micro-structure.

The surface of the extrusions can be seen in the photographs in Figures 7 and 8. In general, all the surfaces were smooth and contained few, if any, longitudinal striations or grooves. All the extrusions had nose bursts, but none had any tears or cracks along the length.

The variations in dimensions are presented in Table 7. In one case, the diameter of the bar varied as much as 0.009 inch from the nose end to the tail end. The lengths and volumes increased with increasing temperature, as did the parameter volume per 1000 foot-pounds. Little or no data exist for the parameter for this molybdenum alloy. Kline[3] reported a value of 0.053 cubic inches per 1000 foot-pounds for unalloyed arc-cast tungsten Dynapak-extruded from 3500°F at a reduction ratio of 4:1. On the assumption that molybdenum would extrude more easily

than tungsten under the same conditions, the parameter values above are slightly lower than would be expected. The differences here might well be explained on the basis of the alloy, lubrication differences, and metallurgical differences in the structure.

Photomicrographs of four of the base-information Dynapak extrusions are shown in Figure 9. The microstructure of the bar Dynapak-extruded from 2840°F shows approximately 10% recrystallization. This temperature was, therefore, too high for the cold working temperature and too low for the intermediate temperature. A bar extruded from 3460°F had a completely recrystallized structure of fine equiaxed grains. Further examination of this micrograph, however, revealed a thin layer of cold worked material at the outer surface of the bar. To remove this layer, but at the same time not use an excessively high temperature, 3500°F was chosen as the hot working temperature. Bar number 8070-6, extruded from 2700°F, showed a completely cold worked structure throughout the cross section of the bar. This temperature was therefore chosen as the cold working temperature. The bar extruded at 2985°F had a surprisingly large amount of recrystallization (80%-90%). On the basis of the microstructure of the bar extruded from 2840°F and the one above, 2950°F was chosen as the intermediate temperature.

Program Extrusions

Surface Evaluation

Photographs of the six press extrusions and six high-velocity extrusions can be seen in Figures 10 through 15. Although some surface detail is lost in the reproduction, the rough surface on the press extrusions is immediately apparent. This roughness was due chiefly to excessive die wear and the subsequent pick-up of die material on the bar surface. All of the press extrusions had transverse tears and cracks on the surface, and all had nose bursts which appeared to be worse in the extrusions made from 2700°F. The two extrusions made from 2700°F had approximately 2 inches of fairly smooth surface at the nose end. Although all the press extrusions had poor surfaces, they could be rated as follows: 3500°F, the best; 2950°F, intermediate; and 2700°F, the worst.

The surface evaluation of the Dynapak extrusions (see Figures 13, 14 and 15) revealed no significant difference in the surface quality of the extrusions made from the three different temperatures nor any difference along the length of the bar. All the surfaces were fairly smooth except for areas speckled with the glass lubricant, and there was no evidence of die material pick-up. All the bars had nose bursts but none had any transverse cracks. There were evidences of some longitudinal grooves which spiralled slightly along the length. There was no pipe in any any of the extrusions since none of the billets were completely extruded.

Dimensions

The variations in dimensions of the Dynapak-and press-extruded bars and the required extrusion energies are shown, respectively, in Tables 7 and 8. The diameters of the press-extruded bars varied greatly along the length and, in one case, the difference was as much as 0.190 inch. This large a diameter change was undoubtedly caused by excessive die wash which resulted from incomplete lubrication

during the extrusion process. In addition, much of the die material seized to the extruded bar and further enlarged the diameter.

The diameters of the Dynapak-extruded bars, shown in Table 7, varied less along the length than did the press-extruded bars. In only one case was the difference between the nose and tail ends as much as 0.016 inch. Note also, that in several cases the diameter was smaller in the center of the length than at either the nose or tail.

K values for the press extrusions were calculated from the equation,

$$P = K \ln \frac{A_o}{A_1},$$

where $\frac{A_o}{A_1}$ is the nominal reduction ratio and P is the peak extrusion pressure. (Actually, the SR-4 pressure cell and Brush oscillograph unit that was used to measure the force did not record a peak in the true sense. Instead, the work "peak" here means the highest force that was recorded and which usually occurred at the beginning of the extrusion process. In only a few cases did this peak force differ significantly from the average force exerted during the extrusion process.) No K value was obtained for billet No. 80 73-4 because of a malfunction of the instrument. The K value for billet No. 80 74-5 is listed as an estimated value because the press was not "bottomed" after this extrusion and, as a result, an accurate force value was not obtained with which to calibrate the recorded curve. In general, the K values varied as expected with temperature, and values in the range of 60,000 to 90,000 psi are in line with data obtained by Tombaugh, et al[4] who reported a value near 100,000 psi for this alloy and similar extrusion parameters.

K values for the Dynapak extrusions were calculated from the equation,

$$\frac{E}{SA} = K \ln \frac{A_o}{A_1},$$

where E is the impact energy delivered by the machine, S is the distance the metal moves, A is the cross-sectional area and $\frac{A_o}{A_1}$ is the nominal reduction ratio. E in this case is the theoretical energy obtained from the adiabatic expansion of the compressed gas rather than the actual energy and is, therefore, necessarily higher than the actual value. However, the K value thus obtained does allow a comparison of the two processes. Note that the K values for the Dynapak process are considerably higher than those calculated for the conventional extrusion process.

Figure 16 shows more clearly the comparison of the K values obtained from each process. In this case, the logarithm of the K value is plotted against the reciprocal of the extrusion temperature. The linear relationship shown in this figure suggests that an equation of the type,

$$K = Ce \exp. \frac{W}{RT}$$

holds for these processes.

The lengths of the bars extruded from both 2700°F and 2950°F on the Dynapak were considerably shorter than expected from previous work. This was caused by a change in the container just previous to the program runs. Rather than 0.005-inch clearance, there was a 0.045-inch clearance between the punch and container. This difference allowed spreading and back extruding of the graphite follow blocks, with a subsequent increase in friction along the container walls and reduction in the energy available for extruding the billet. As a result the parameter volume per 1000 foot-pounds was lower for the program extrusions than for the base-information extrusions. In addition, the die bore size was slightly larger, which reduced the reduction ratio and decreased the length.

The difference in die wear that occurred during press extruding and Dynapak extruding can best be demonstrated in Table 9 which shows the die bore diameter before and after extruding. The excessive die wear that occurred during press extruding can be seen in Figure 17.

Chemistry

The results of the oxygen and nitrogen analyses taken from the nose and tail ends of the extrusion are shown in Tables 10 and 11. All the values are low and show no significant difference between the ends of the bars. Higher oxygen contents are shown for the Dynapak-extruded bars, but these small differences can possibly be explained on the basis of original ingot chemistry or by inaccuracies in analyses performed at low interstitial levels.

Hardness

The results of the hardness determinations for the high-velocity and press extrusions are shown in Tables 10 and 11, respectively. Both the transverse and longitudinal sections show a decrease in hardness with increasing extrusion temperature. The transverse hardness of the Dynapak extrusions made from 3500°F and 2950°F are slightly lower than the press extrusions made from these temperatures and can be explained by the microstructure discussed below. The difference in hardness between the center and the edge of both types of extrusions can also be explained by the microstructure, and this indicates a greater amount of working at the edge than in the center. This fact may only be significant for small extrusion ratios such as the 4:1 ratio used in this work.

Tensile Properties

The room temperature tensile test results for the as-extruded material, Tables 12 and 13, indicate higher strengths for the press-extruded bars than for the Dynapak-extruded bars extruded from the same temperature. Room-temperature tensile strengths of 82,500 psi and 92,100 psi shown for the material press-extruded from 2700°F are slightly lower than expected for this alloy. For example, DMIC Report 140[5] indicates an ultimate strength of 105,000 psi for a 1/2-inch diameter rolled bar in the recrystallized condition. The room temperature tensile test results for the annealed material also show higher strengths for the press-extruded bars than the Dynapak-extruded bars. It is interesting to note that the strength values of the annealed material are higher than those of the as-extruded material for both the Dynapak- and the press-extruded bars. This fact can possibly be explained by the

increased ductility of the annealed material which allows the tensile specimens to reach higher strength levels before fracture occurs. Since many of the specimens broke in the threads, all the values are subject to question and no valid comparisons can be made.

The button head specimen used for the 2000°F tensile tests did not break out of the gauge length and a more valid comparison can be made. In this case, however, little difference is shown between the Dynapak-extruded bars and the press-extruded bars in either the as-extruded condition or the annealed condition when extruded from the same temperature. Ultimate strengths in the range 44,300 to 50,000 psi for the press-extruded material appear to fall in between data given in DMIC Report 140 for recrystallized material at 1800°F and 2400°F. Figure 18 shows the 2000°F tensile data for as-extruded material as a function of hardness and shows more clearly the similarity of the tensile properties of Dynapak- and press-extruded material when extruded from the same temperature. Note also, however, that at the same strength level, the press-extruded material is harder; or, conversely, at the same hardness level, the Dynapak-extruded material is stronger.

Microstructure

Photomicrographs taken at the center of the cross section of the six press extrusions and six Dynapak extrusions are shown, respectively, in Figures 19 and 21. It is clear, from Figure 19, that the three chosen extrusion temperatures did not produce the three desired types of microstructure in the press extrusions. A much more cold worked structure was obtained than indicated by the evaluation of the base-information Dynapak extrusion. Even at 3500°F, the press extruded material was only approximately 50% recrystallized.

The photomicrographs of the Dynapak extrusions in Figure 21, however, do show the desired structures. Material extruded from 3500°F consists of completely recrystallized fine equiaxed grains. Material extruded from 2950°F contains a mixture of cold worked and recrystallized grains, and material extruded from 2700°F consists of a completely cold worked structure.

Figure 20 shows three photomicrographs of press-extruded material. Photomicrographs "A" and "B" were taken at the tail end within 1 inch of the bottom of the pipe of one of the extrusions made from 2700°F. Photomicrograph "A", which was taken near the surface, shows the expected cold worked structure. Photomicrograph "B", on the other hand, shows material at the center of the cross section. Here is revealed undeformed as-cast grains (see Figure 2) which indicate that some difficulties might arise when using small reduction ratios, i.e., the surface of the extrusion is more highly worked than the center, and some portion of the tail end is not worked at all. Micrographs taken at the nose end also revealed areas of undeformed as-cast grains. Photomicrograph "C" was taken at 500X to show the partial recrystallization that did occur in material press-extruded from 2950°F.

Figure 22 shows two photomicrographs of Dynapak-extruded bars. Photomicrograph "A", which was taken near the surface of the same cross-section shown for this bar in Figure 21, again reveals the increased amount of cold work near the surface of the bars which accounts for the increased hardness values shown in Table 10. Photomicrograph "B" is presented to show the thin layer of cold worked

material at the surface of material Dynapak-extruded from 3500°F and the sharp transition from cold worked material to completely recrystallized material. This thin layer of cold worked material results from the loss of temperature to the tooling.

Recrystallization Evaluation

All specimens, from the press-extruded and Dynapak-extruded bars, which were heat treated for one hour were examined for microstructure. The most significant results of this evaluation are shown in Figure 23 for the press-extruded material, and Figure 24 for the Dynapak-extruded material. Figure 23 shows that only small changes occur in the press-extruded material when heat treated for one hour at 2900°F. By comparing Figure 23 with Figure 19, slight change in the material extruded from 2700°F can be seen in the form of larger cold worked grains, but no significant change is evident in the material extruded from 3500°F.

The microstructures shown in Figure 24 reveal that material Dynapak-extruded from 2700°F will completely recrystallize when heat treated for one hour at 2900°F. When comparing Figure 24 with Figure 21, it can be seen that little change occurred in the material extruded from 2950°F and only a slight enlargement of the grains in the material extruded from 3500°F.

Figure 25 shows the change in hardness that takes place as a result of annealing treatments. In most cases the hardness decreased after annealing, but only the material Dynapak-extruded from 2700°F showed a sharp drop near the annealing temperature of 2900°F, and this was the result of the complete recrystallization discussed previously.

DISCUSSION

Three significant criteria can be used to compare high-velocity extrusions with press extrusions. These criteria are: surface and dimensions, as-extruded microstructure, and recrystallization behavior.

The surface of the extrusions was the first most obvious difference. While the surfaces of the Dynapak extrusions were fairly smooth and crack-free, the surfaces of the press extrusions were rough, were covered with die material, and had transverse tears along the length. This large a difference in surface quality is not believed to be inherent in the processes themselves, but instead is due to a combination of inadequate die preparation and lubricating technique, and the longer time of contact between hot metal and tooling during the conventional extrusion process. As a result, the extrusion-press dies washed badly and produced extrusions with poor surfaces. In the Dynapak process, this contact time is shorter and, although the die preparation and lubricating techniques were the same as for conventional extrusions, die wash was less and the extrusion surfaces were better. With optimum die preparation and lubricating techniques for each process, the difference in surface quality and dimensions should be minimized.

A comparison of the as-extruded microstructure indicates that lower hot working temperatures can be used for Dynapak extruding than for conventional press extruding. This fact is explained by two differences in the processes: one, the

working rate and, two, the actual temperature of the billet during the extrusion operation. In the first case, the working rate of the high-velocity process can not only raise the temperature during extrusion, but can produce sufficient work of high enough stress (at a time when the temperature is still sufficiently high) to cause recrystallization. The actual temperature of the billet during extrusion is a function of the furnace temperature, the transfer time, and the heat loss during the operation. The first two variables were kept substantially the same. The third variable, however, is quite different in the two processes. The large mass of the press container and the relatively long time for the extruding operation lowers the billet temperature and thus prevents recrystallization of the worked material.

A comparison of the recrystallization behavior of the extruded material indicates that the Dynapak-extruded bars receive a higher degree of stress than do the press-extruded bars. This is evidenced by the fact that when extrusions are cold worked from the same temperature on each machine, the Dynapak-extruded material has the lowest recrystallization temperature. One would expect this higher state of stress to substantially increase the hardness and tensile properties. However, this was not the case. A second explanation for the difference in recrystallization behavior is the difference in cooling rate between extrusions from each process. In the Dynapak process, where the extrusion was not completed, the extruded bar hung in the die and was air cooled and partially cooled by the tooling. In the extrusion press process, the completely extruded bar was immediately placed into an insulating material, e.g., fuller's earth, and allowed to cool slowly. This, of course, provided partial stress relief. As a result, a higher temperature is needed for recrystallization for the press extrusions.

One other comparison can be made for the lengths of the extruded bars. The extrusion press extruded the full lengths of billets used in this program and could extrude even longer billets. The Dynapak, however, did not completely extrude any of the billets and, although the correct combination of fire pressure, billet length, and temperature could be determined to completely extrude a billet, there is a definite limit to the volume of material which can be extruded on the Dynapak as there is for all extrusion machines.

PHASE II TUNGSTEN ALLOY EXTRUSIONS

RESULTS

Base Information Extrusion

As for the molybdenum extrusions in Phase I, this part of Phase II was designed to establish three temperatures which would produce, respectively, 100% hot work, 100% cold work, and a structure containing approximately 50% recrystallization. The evaluation of these base information extrusions was limited, therefore, to surface quality, dimensions, and microstructure.

The surface of the extrusions can be seen in the photographs in Figures 26 and 27. The three extrusions from 3900°F, 3440°F, and 3200°F had very smooth surfaces containing very shallow, if any, longitudinal striations. The three extrusions

from 3000°F, 2800°F, and 2600°F had somewhat rougher surfaces and the longitudinal striations were more pronounced. All the extrusions had nose bursts which appeared to become worse as the extrusion temperature was lowered. None of the extrusions contained any transverse cracks and only bar KC 1091 B contained a longitudinal crack which propagated an appreciable distance. Bars KC 1091 B and KC 1092 A broke while being removed from the die.

The variations in dimensions are presented in Table 14. In most cases the bar diameter varied only 0.004 to 0.006 inch from the nose end to the tail end. In one case, bar KC 1092 A, the tail end was 0.015 inch larger. This resulted from the low temperature extrusion abrading the oxide coating, thereby enlarging the die bore size. The lengths and volumes increased with increasing temperature as did the parameter volume per 1000 foot-pounds. These parameter values are higher than would be expected from examining data of Kline(3) who reported a value of 0.053 cubic inch per 1000 foot-pounds for arc-cast unalloyed tungsten Dynapak-extruded from 3500°F at a reduction ratio of 4:1. The higher value reported here might well be explained by differences in die preparation and lubrication techniques or by metallurgical differences in the as-cast structure. The fact that this material is alloyed would lead one to expect a lower value because of its greater resistance to deformation.

Photomicrographs of the six base information Dynapak extrusions are shown in Figure 28. The microstructures of the bars extruded from 3900°F, 3440°F, and 3200°F revealed a completely recrystallized structure of fine equiaxed grains and 3400°F was chosen as the hot working temperature. The microstructures of the bars extruded from 2800°F and 2600°F both showed a completely cold worked structure throughout the cross-section of the bar, and 2800°F was chosen as the cold working temperature. Bar KC 1091 A, extruded from 3000°F, contained 10% to 40% recrystallized grains and 3000°F was, therefore, too low for the intermediate range. On the basis of this microstructure and that of the bar extruded from 3200°F, 3100°F was chosen as the intermediate extrusion temperature.

Program Extrusions

Surface Evaluation

Photographs of the seven press extrusions and six Dynapak extrusions can be seen in Figures 29 through 34. The smooth surfaces of the press extrusions are readily apparent and are the result of using ceramic-coated dies. All of the press extrusions had small nose bursts and a deep pipe at the tail end, but none had any transverse tears or cracks. They had, however, some longitudinal cracks in the tail end which became less severe as the extrusion temperature was raised. Aside from the nose bursts and cracks, there was no obvious difference in the surface appearance of the extrusions as a result of extruding from different temperatures.

In contrast with the molybdenum program, the Dynapak-extruded tungsten bars had a poorer surface than the press-extruded bars. All the bars contained longitudinal striations and all had nose bursts. The severity of the nose bursts of the bars does not appear to have any relationship to the extruding temperature. There was no pipe in any of the extrusions since none of the billets were completely extruded, nor does the surface quality change appreciably with extrusion temperature.

Ultrasonic tests were made on both the press and Dynapak extrusions. The extent of the pipe and nose bursts in the press extrusions was readily detected and these areas were removed. Small indications were revealed in bar KC 1111 A approximately 1/4 inch in from the surface which were removed in subsequent machining of tensile specimens. Bar KC 1109 B contained a crack extending eleven inches from the tail end. This crack was in the center of the bar and was removed when the bar was longitudinally halved for tensile specimens. The extent of the nose bursts in the Dynapak extrusion was readily detected and these areas were removed. Only two Dynapak-extruded bars had any indication of defects. These defects were very close to the bar surface and, therefore, presented no problem.

Dimensions

The variations in dimensions of the Dynapak- and press-extruded bars and the required extrusion energies are shown, respectively, in Tables 14 and 15. The diameters of the Dynapak-extruded bars were quite uniform on four of the bars, varying only 0.002 to 0.005 inch over the length. In two of the bars, however, the diameter varied over 0.010 inch over the length. The diameters of the press-extruded bars were likewise quite uniform, varying 0.005 inch or less along the length. Only one bar, KC 1111 B, had a difference of 0.014 inch between the nose end and tail end. The uniformity of the tungsten press extrusions, in contrast to the molybdenum extrusions, was due mainly to the ceramic coating used on the dies.

K values for the Dynapak and press extrusions are shown in Tables 14 and 15 and were calculated in the same way as for the molybdenum extrusions. On the average, the K values for the press extrusions varied with temperature as anticipated, and are similar to those reported in the literature[(4)], although somewhat lower. K values for the Dynapak extrusions also decreased, as expected, with increasing temperature. Little or no data exist with which to compare these values. Figure 35 more clearly shows the relationship between K values and the extrusion temperature, and the difference in K values for the Dynapak and extrusion processes. In contrast to the molybdenum curves, the relationship of the logarithm of the K values to the reciprocal of the temperature is not linear. This suggests that the simple relationship between K and absolute temperature does not apply here and that other forces, e.g., frictional forces, are affecting the extrusion pressure. Note also the high K value, 91,200 psi, for billet 1086 B for which the transfer time from furnace to press was 20 seconds.

The lengths of the Dynapak extrusions were slightly shorter than expected from the base information runs and is not understood at this time. As a result, the parameter volume per 1000 foot-pounds was also lower than would be expected. This parameter, however, was still in line with Kline's[(3)] data.

The extrusion press dies and Dynapak dies are shown, respectively, in Figures 36 and 37. Figure 36 shows the fairly smooth ceramic coating remaining on the press dies with only a few areas "flaked" out. The Dynapak dies, however, had large areas of ceramic coating removed which made it difficult to obtain die bore dimensions after extruding. Table 16 lists the changes in the die bore diameter as a result of press extruding.

Chemistry

The results of the oxygen and nitrogen analyses taken from the nose and tail ends of the extrusions are shown in Tables 17 and 18. No significant difference was observed between the ingots and the extruded bars or between the press-extruded and Dynapak-extruded bars. No special significance can be placed on the small differences shown in the tables because, although the precision is good (see footnote 1, Table 1), the accuracy of the analyses at these low levels has not been established.

Hardness

The results of the hardness determinations for the Dynapak and press extrusions are shown in Tables 17 and 18. Standard steel hardness conversion tables were used where necessary to convert from the scale used to the DPH number. There does not appear to be any relationship between the as-extruded hardness and the extrusion temperature for either the Dynapak extrusions or the press extrusions, nor does the edge hardness appear to be consistently higher or lower than the center. On the average, the Dynapak extrusions appear harder than the press extrusions. There does appear to be some evidence that the hardness of the center of the press-extruded bar lengths is lower than either end. No hardness readings were obtained at the center of the Dynapak-extruded bars because they were too short.

Tensile Properties

The room temperature tensile test data for the as-extruded material, Tables 19 and 20, indicate a higher strength for the press-extruded bars than for the Dynapak-extruded bars extruded from the same temperature. The limited data and large spread in values preclude a significant comparison. The room temperature data for the annealed material do not have such a wide spread in values and indicate a higher strength for the Dynapak-extruded bars. In contrast to the tensile tests on molybdenum, annealing this tungsten alloy reduces the room temperature tensile strength and does not increase the ductility. This is caused by the complete recrystallization of all the extrusions when annealed at 3000°F (see below).

The 3000°F tensile test results reveal little significant difference between the Dynapak-extruded bars and the press-extruded bars extruded from the same temperature. Ultimate tensile strengths in the neighborhood of 40,000 psi compare favorably with data of McKinsey, et al[6] who reported a value of 42,500 psi for as-extruded material. A tensile strength of 51,000 psi for the material press-extruded from 2800°F can not be explained at this time.

The change in 3000oF tensile strength with hardness is shown in Figure 38 which also shows the increase in tensile strength with decreasing extrusion temperature.

Microstructure

Photomicrographs taken at the center of the cross-section of the seven press extrusions and six Dynapak extrusions are shown, respectively, in Figures 39 and 41. It is seen from Figure 39 that the three chosen extrusion temperatures did not produce, in the press extrusion, the three desired types of microstructure.

Considerably more cold work appears in the bars extruded from 3100°F and 3400°F than would be indicated by the base information Dynapak extrusion.

The photomicrographs of the Dynapak extrusions in Figure 41, however, do have the desired structures. Material extruded from 3400°F consists of completely recrystallized, fine equiaxed grains. Material extruded from 2800°F consists of completely cold worked grains, and the bars extruded from 3100°F contain approximately equal amounts of cold worked and recrystallized grains.

Figure 40 shows five photomicrographs of press-extruded material. Picture A shows the center section of the second tungsten bar extruded from 3400°F following rapid transfer from furnace to press, and shows a greater degree of recrystallization than does bar KC 1086 B for which the transfer time was 20 seconds (see Figure 39). Photograph B shows the same bar, but an area near the surface. There can be seen a greater degree of cold work and fine recrystallized grains. Photos C and D are the nose end and tail end, respectively, of bar 1111 AD. A comparison of these two with the same bar in Figure 39 reveals no recrystallization at the nose end and approximately the same degree of recrystallization at the tail end as in the center. Photograph E at 500X shows more clearly the recrystallization that took place in bar KC 1110 B which was extruded from 3100°F.

Figure 42 shows four photomicrographs of Dynapak-extruded bars. A comparison of these photographs and those of Figure 41 suggests a higher degree of working at the surface of the bars and the effect of heat loss at the nose end of the extrusions. Note the banded structure in photograph C.

Table 21 summarizes the results of the evaluation of the microstructure and shows the greater amount of recrystallization that occurred as a result of Dynapak extruding.

<u>Recrystallization Behavior</u>

All the specimens from the press-extruded and Dynapak-extruded bars were heat treated for one hour at 2700°F, 2850°F, 3000°F, 3150°F, or 3300°F. Each of these were examined for microstructure and hardness. Figures 43 and 44 show the most significant results for the press-extruded and Dynapak-extruded bars, respectively. Photomicrograph A in Figure 43 shows that essentially no recrystallization took place in the bar press-extruded from 2800°F and annealed at 2700°F. At 2850°F, however, a bar extruded from 2800°F became completely recrystallized. Material extruded from 3400°F completely recrystallized at 3000°F, but not completely at 2850°F.

The photomicrographs of the annealed Dynapak extrusions, in Figure 44, indicate that material extruded from 2800°F became approximately 50% recrystallized when annealed at 2700°F (photograph A) and 100% recrystallized when annealed at 2850°F. Material extruded from 3100°F was approximately 75% recrystallized when annealed at 2850°F. Annealing material Dynapak-extruded from 3400°F merely tended to enlarge the grain size. Compare the grain size in photographs D and E with those in Figure 41.

Annealing either the press extrusions or the Dynapak extrusions at 3150°F and

3300°F effected complete recrystallization.

A plot of hardness vs annealing temperatures is shown in Figure 45. Although there is a general reduction in hardness as a result of annealing, there appears to be no discrete decrease in hardness with increases in annealing temperature. Since the specimens for this work were taken from identical locations in the extrusions, it would appear that the fluctuations in hardness reflect ingot-to-ingot variations.

DISCUSSION

There are two distinct differences between the high energy rate process and the conventional extrusion process. One, of course, is the rate of metal working. The high metal working rate of the Dynapak allows less time for heat transfer to the tools, increases the metal temperature, and appears to impose a higher internal stress in the material. The second difference is the cooling rate of the extrusion. In the conventional process, the tungsten extrusions are removed from the run-out table and immediately placed into a trough of insulating material (vermiculite, fuller's earth, etc.). In the Dynapak process, the extrusion is air cooled because it hangs in the die (in this work) and part of it remains in contact with the die. This difference in cooling rate allows differences in stress relief and, therefore, differences in the state of residual stress.

None of the above differences appear to affect the surface of the extrusions when proper lubrication techniques are used. In contrast to the molybdenum extrusions, there was little difference between the surface of the tungsten Dynapak and press extrusions. This similarity was due primarily to the ceramic coating used on the dies. This ceramic coating acted as a heat barrier and, in conjunction with the graphite on the die and glass on the billet, provided sufficient lubrication for both processes. This suggests that equally good surfaces can be obtained by both processes when the best lubrication techniques are used. Lubrication techniques also affect dimensional variations and it appears that equally good dimensional tolerances can be obtained by both processes.

The metal working rate and extrusion cooling rate significantly affect the hardness, microstructure, recrystallization behavior, and tensile properties of the tungsten extrusions. For equal extrusion temperatures, if the extrusions from both processes have a cold worked structure, the Dynapak extrusions will be harder, stronger, and will recrystallize at a lower temperature. For slightly higher extrusion temperatures, again both being equal, the Dynapak extrusions will be recrystallized, but in this case the conventional extrusions will be harder and stronger.

The results of this work suggest that the terminology "cold work" must be further defined when discussing metal working operations at elevated temperatures. Both the temperatures of the operation and the rate of metal working affect the state of residual stress and the subsequent metallurgical behavior and should therefore be stated. The data also suggest the existence of a powerful tool for controlling the hardness level, recrystallization behavior, and, therefore, the elevated temperature strength of refractory materials.

GENERAL CONCLUSIONS

1. At least twelve cubic inches of three-inch diameter arc-cast Mo-25W-0.1Zr or W-0.6Cb alloy billets can be extruded at a 4:1 reduction ratio in the cold worked condition on a Model 1810 Dynapak machine. This volume can be raised to over twenty cubic inches if higher extrusion temperatures are used.

2. The high-velocity process and the conventional extrusion process can produce equally good surfaces on extrusions when proper die preparation, die coating, and lubrication techniques are used.

3. The extrusion temperature required to break up the as-cast grain structure into fully recrystallized material is lower for the high-velocity process than for the conventional extrusion process.

4. In the cold working temperature range, the high-velocity process produces harder and stronger extrusions than does the conventional extrusion process.

5. The recrystallization temperatures for high-velocity-extruded material are lower than those for conventionally extruded material.

RECOMMENDATIONS

1. The extrusion billets for this work were all of as-cast material. Since the high-velocity process can serve as a secondary working process as well as a primary process, the effect of this process on as-forged or extruded material should be investigated.

2. A significant difference in substructure may result from variations in the rate of metal working, and may be detected by a more critical examination of the microstructure at high magnifications.

REFERENCES

1. Reimann, G. A., Interim Report 7-882(I), "High Energy Rate Extrusion", USAF Aeronautical Systems Center, Westinghouse Electric Corporation - Contract AF 33(600)-41948.

2. Vandergrift, E. F., "Metal Testing at High Temperatures", ASME Publication - Paper No. 62 - Met 6. April 9-13, 1962.

3. Kline, J. A., "Dynapak Extrusions", pamphlet by Convair Division of General Dynamics Corporation, San Diego, California, September, 1960.

4. Tombaugh, et al, "Development of Optimum Methods for the Primary Working of Refractory Metals", WADD Technical Report 60-148, Part II - August, 1961.

5. Houck, J. A., "Physical and Mechanical Properties of Commercial Molybdenum-Base Alloys", DMIC Report 140, Battelle Memorial Institute, Columbus, Ohio - November 30, 1960.

6. McKinsey, C. R., et al, "Investigation of Tungsten - Tantalum - Columbium - Base Alloys", WADD Technical Report 61-3 - July, 1961.

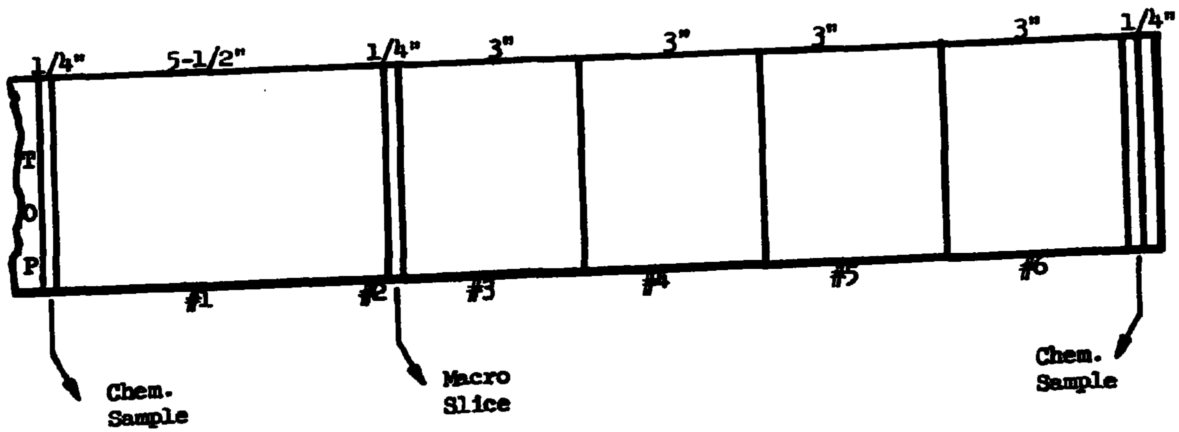


FIGURE 1 - Sketch Showing the Position of Billets, Macro Slices, and Chemical Analysis Samples in the Original Ingot

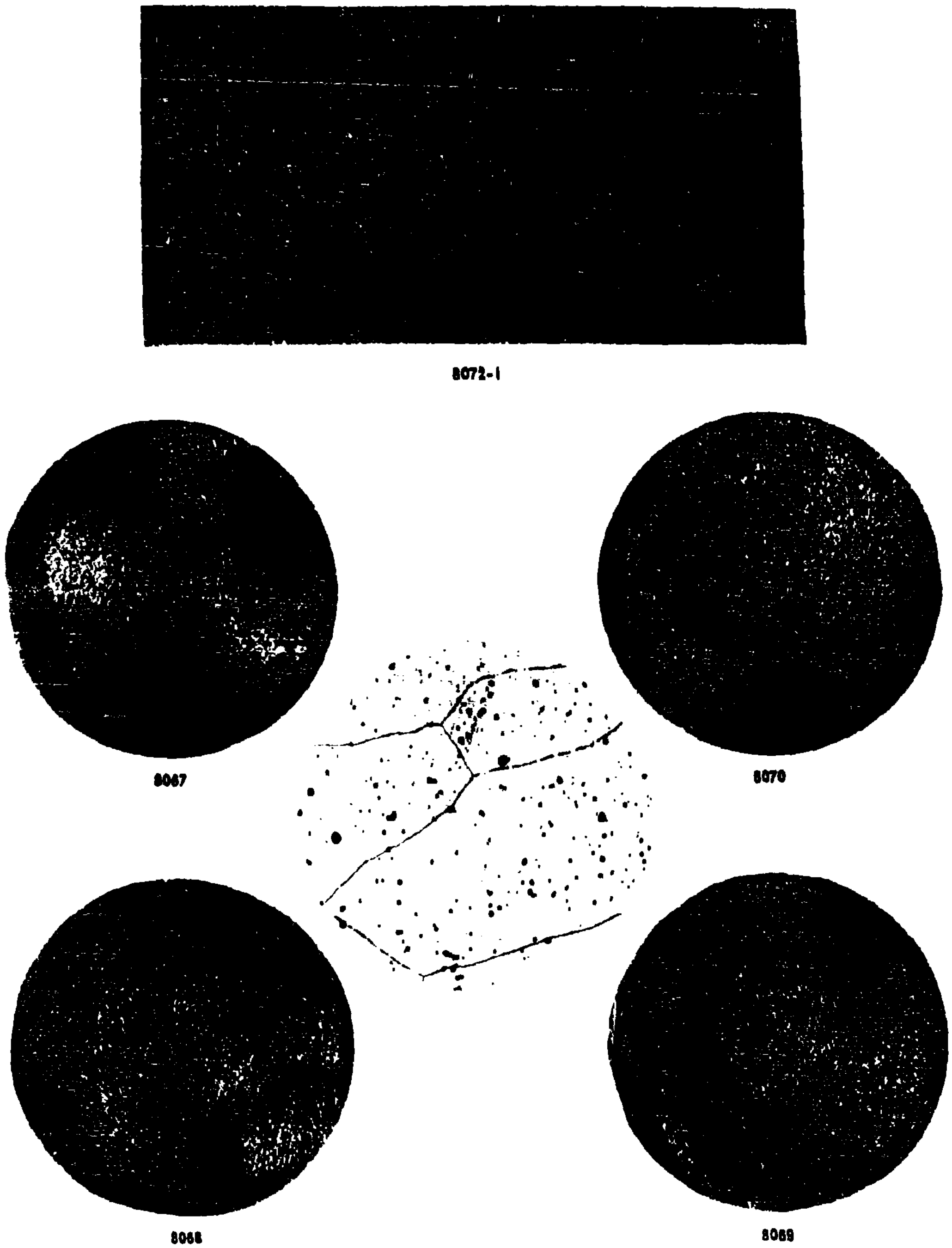


FIGURE 2 - Examples of Longitudinal and Transverse Macrostructure and Longitudinal Micro-Structure (100X) of As-Cast Molybdenum Alloy Ingots

KC 1084
TRANSVERSE MACROSTRUCTURE

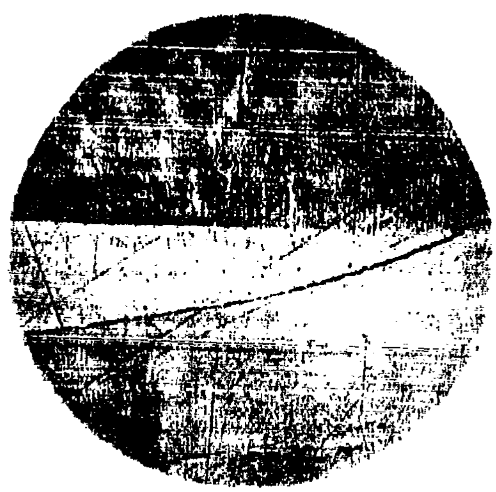


FIGURE 3 - Example of Transverse Macostructure and Longitudinal Microstructure (100X) of As-Cast Tungsten Alloy Ingots.

FIGURE 4 - General View of 700-Ton Loewy High Speed Extrusion Press Showing Proximity of Billet Heating Furnace

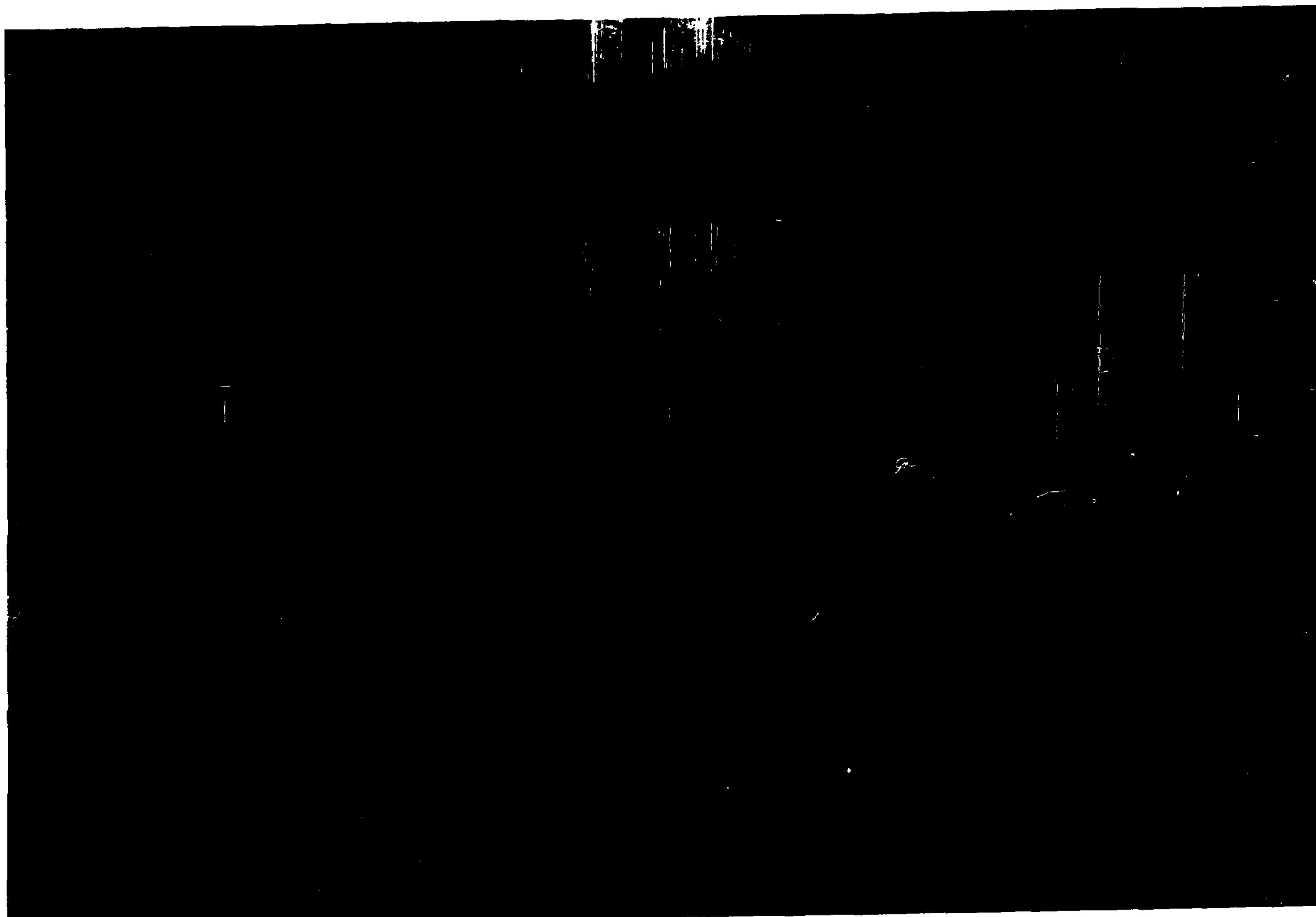
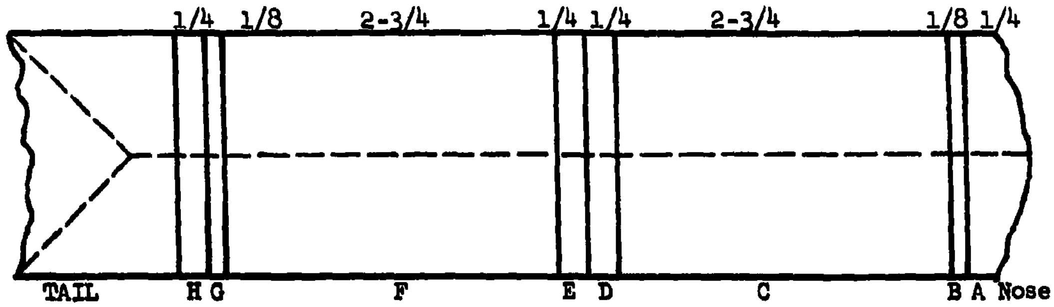
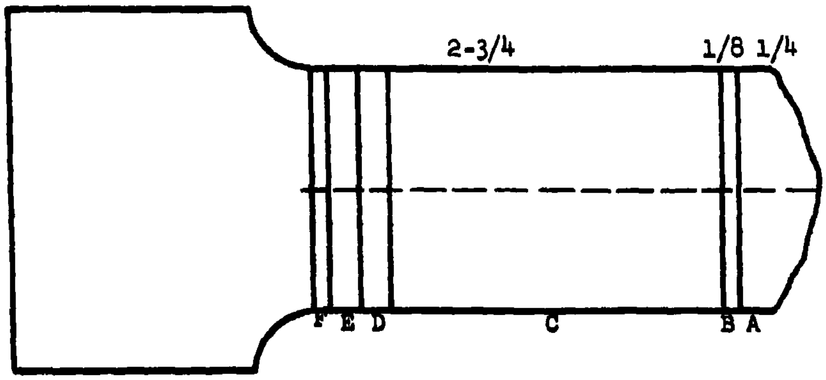


FIGURE 5 - General View of Model 1810 Dynapak Machine Showing Proximity of Billet Heater Furnace



Sampling Technique For High Speed Press Extrusions



Sampling Technique For Dynapak Extrusions

Code:

A. Longitudinal micrographic sample.
B. O_2 and N_2 gas samples.
C. Tensile specimens.
D. Longitudinal micrographic sample, micro hardness sample, Rockwell B hardness, and two recrystallization samples.
E. Recrystallization samples.
F. (Press) Tensiles.
F. (Dynapak) O_2 and N_2 gas samples.
G. O_2 and N_2 gas samples.
H. Longitudinal micrographic sample.

FIGURE 6 - Sampling Technique Used for the High Speed Press and Dynapak Extrusions

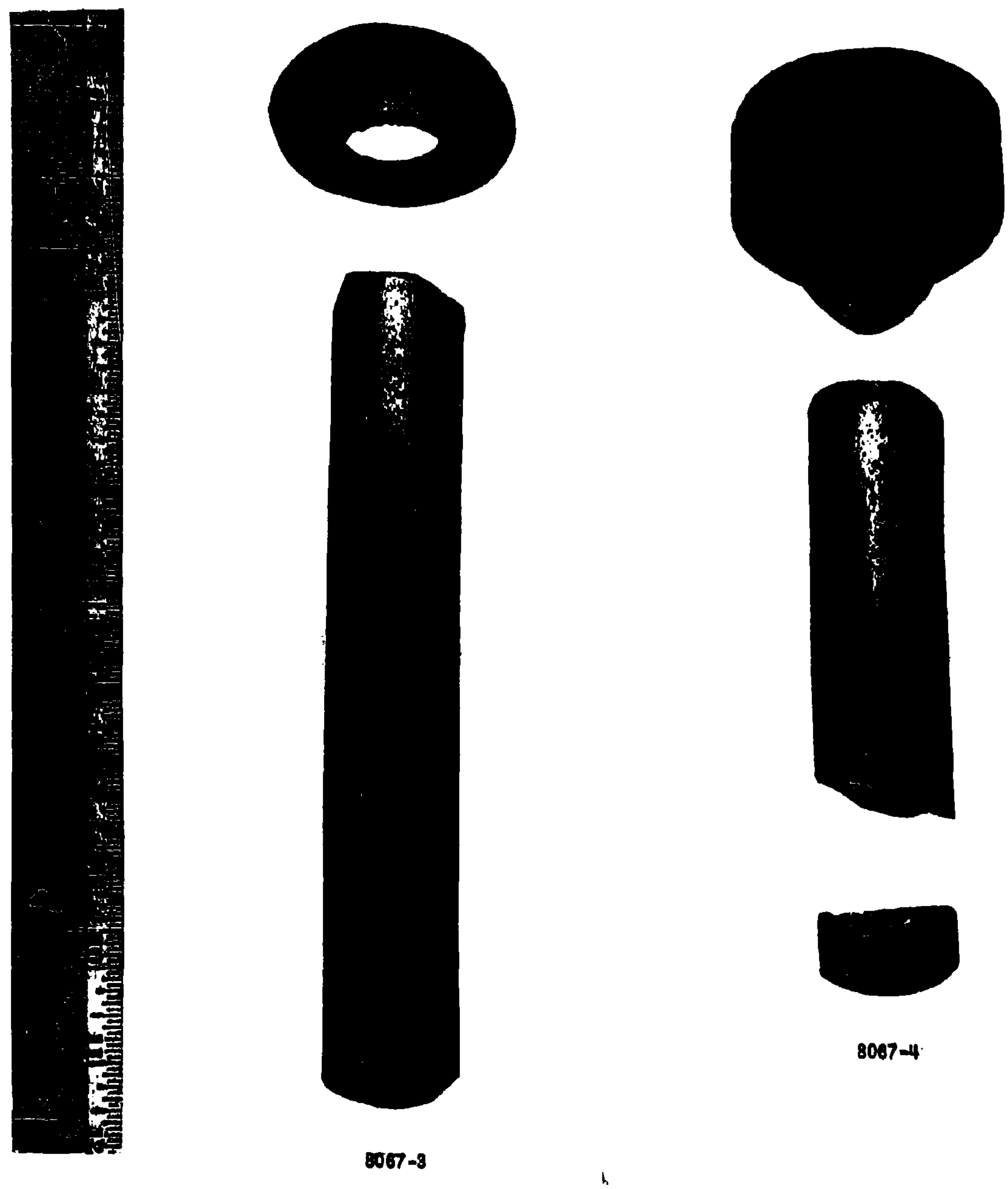


FIGURE 7 - Base Information Dynapak Extrusion in the As-Extruded Condition

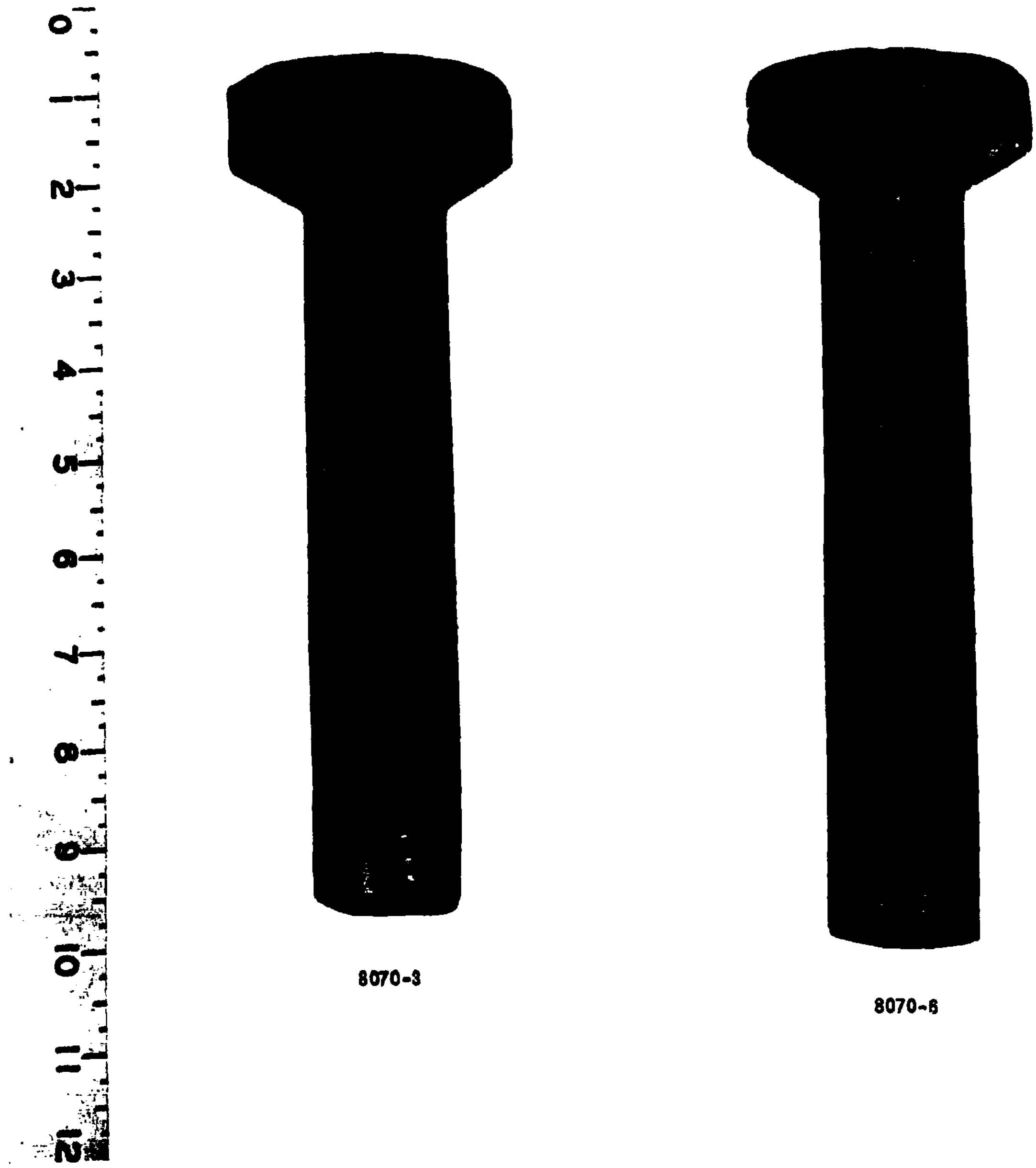
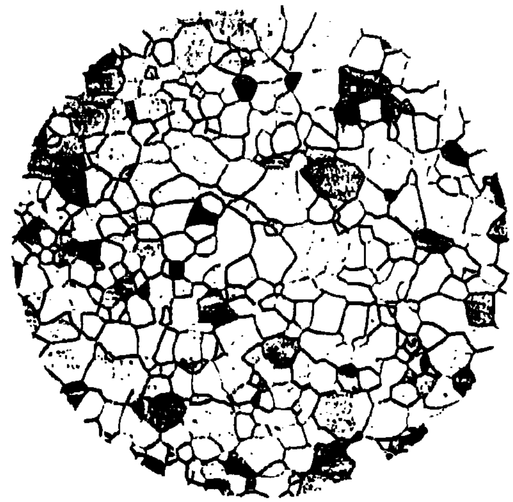


FIGURE 8 - Base Information Dynapak Extrusions in the As-Extruded Condition

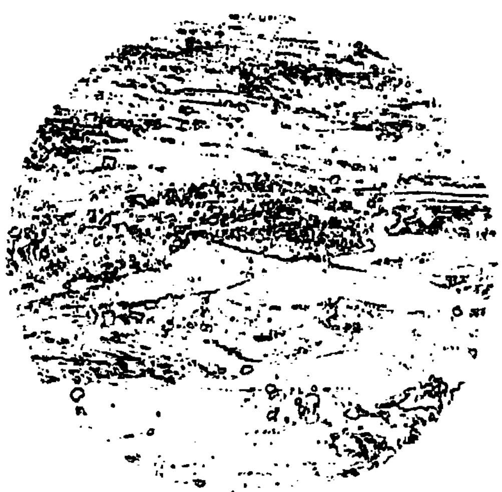
8067-4

2840°F



8070-4

3460°F



8070-6

2700°F

8069-4

2985°F

FIGURE 9 - Longitudinal Micrographs (100X) and Extruding Temperatures of Base-Information Dynapak Extruded Molybdenum Alloy Bars

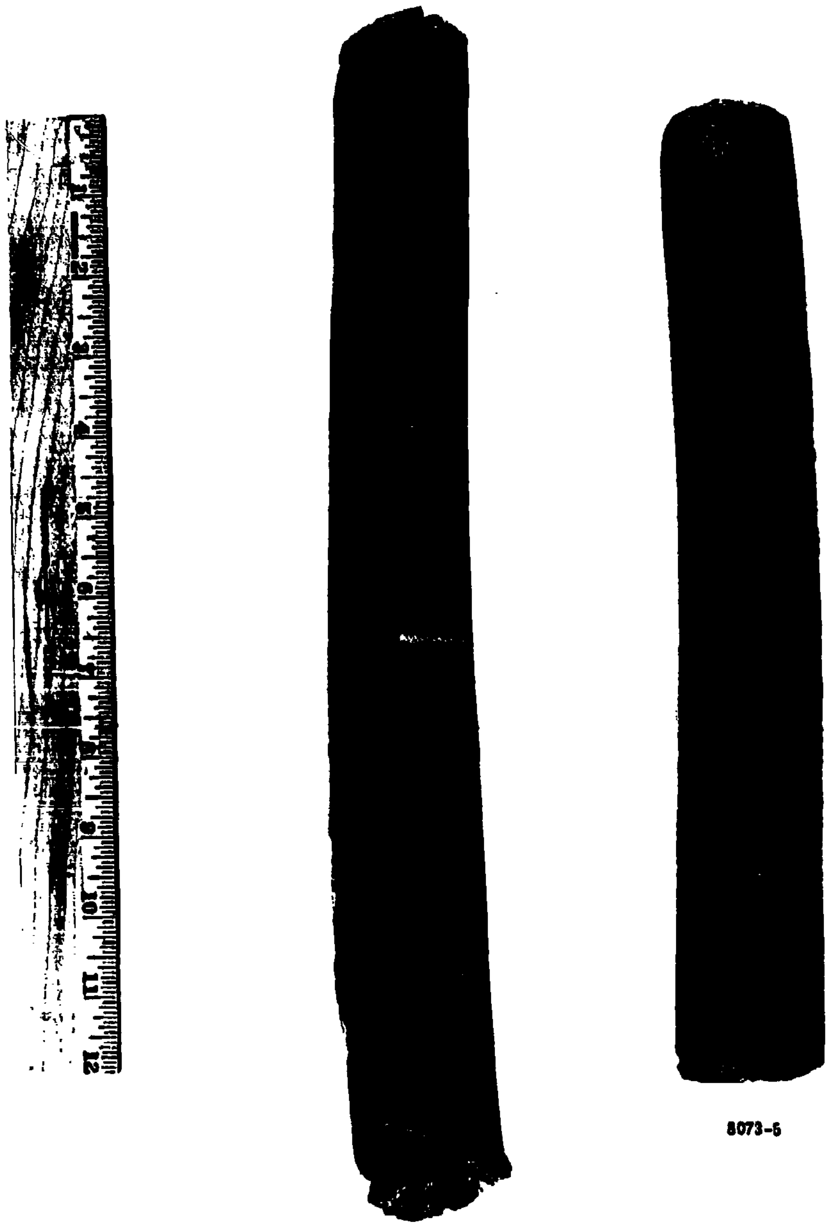
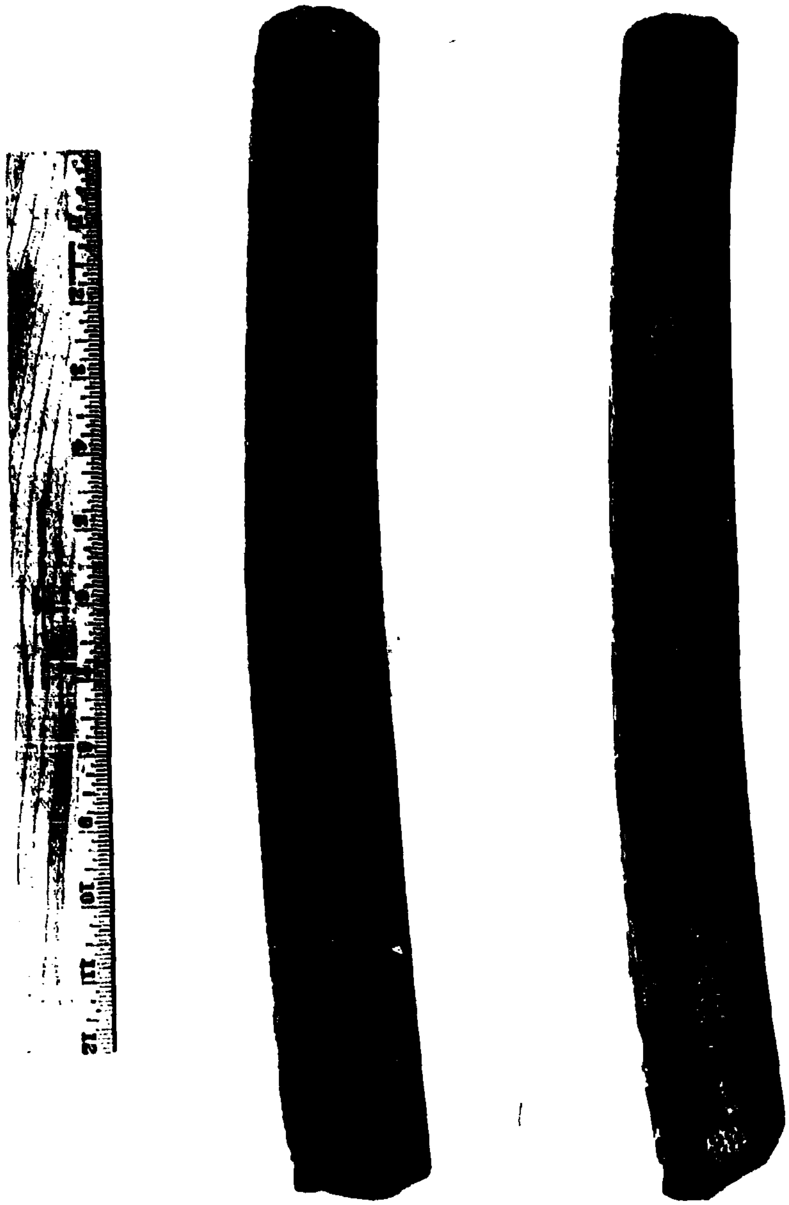


FIGURE 10 - High Speed Press Extruded Bars. As Extruded from 2700°F



8073-1 8074-5

FIGURE 11 - High Speed Press Extruded Bars. As Extruded from 2950°F

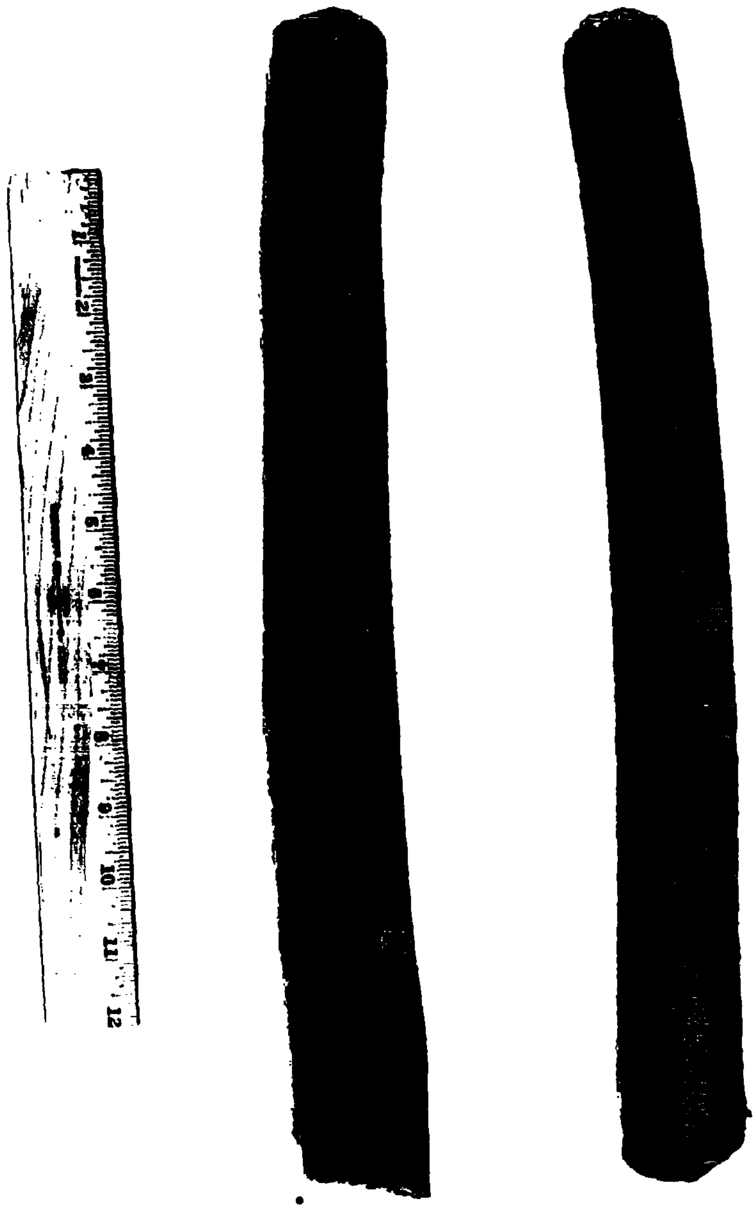


FIGURE 12 - High Speed Press Extruded Bars. As Extruded from 3500°F

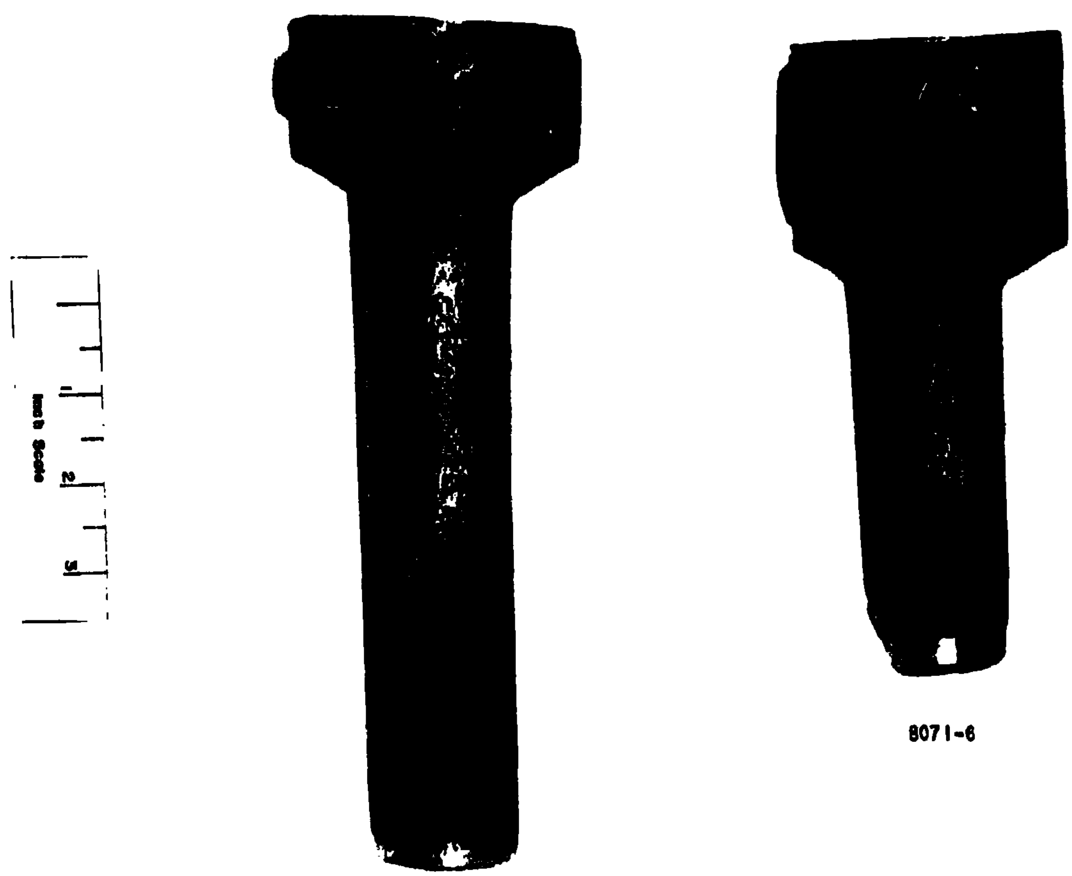
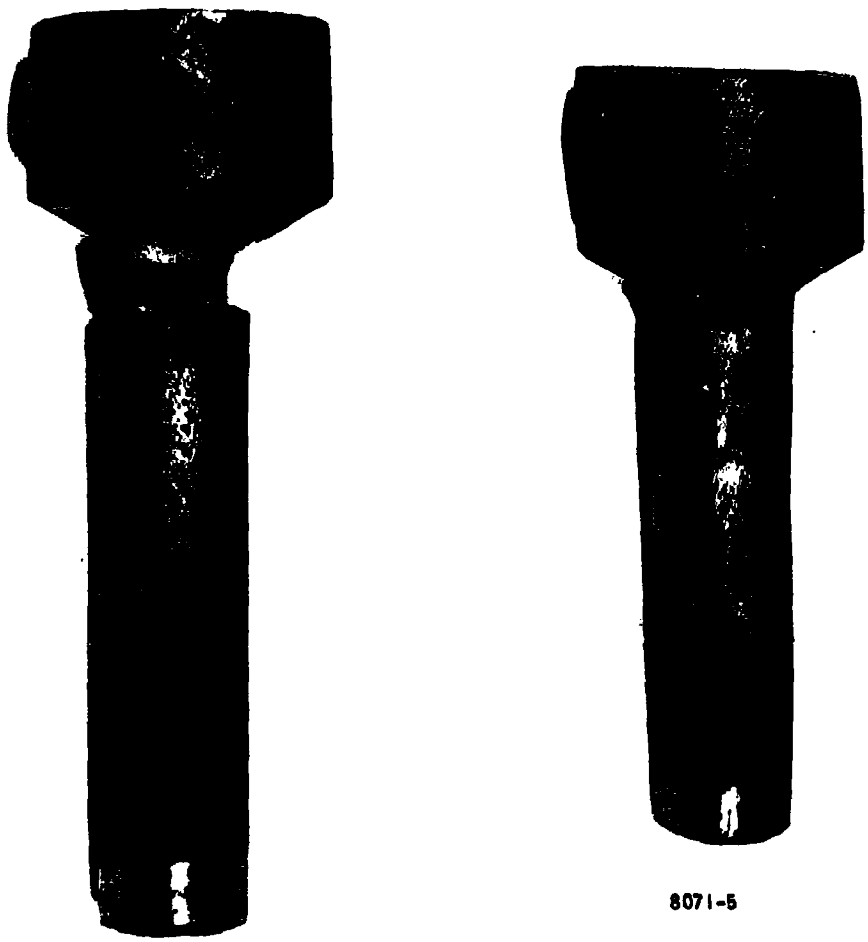


FIGURE 13 - Dynapak Extruded Bars. As Extruded from 2700°F



8072-3

8071-5

FIGURE 14 - Dynapak Extruded Bars. As Extruded from 2950°F

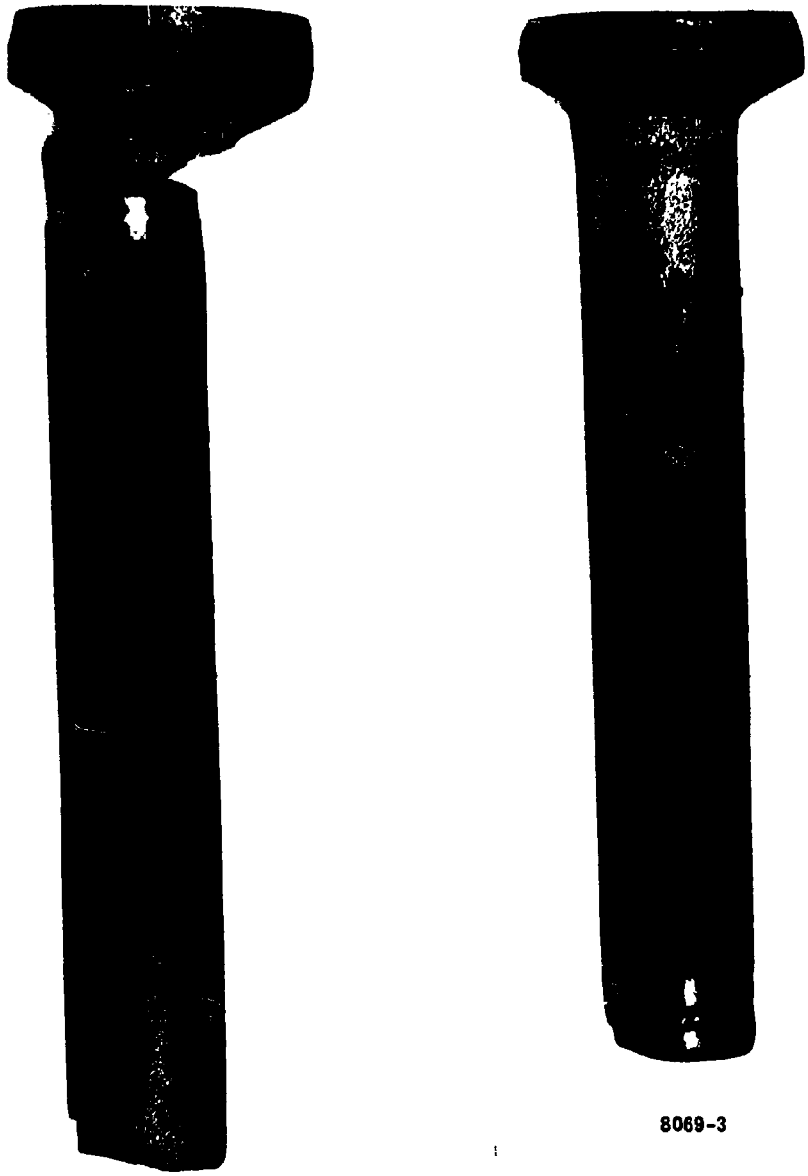


FIGURE 15 - Dynapak Extruded Bars. As Extruded from 3500°F

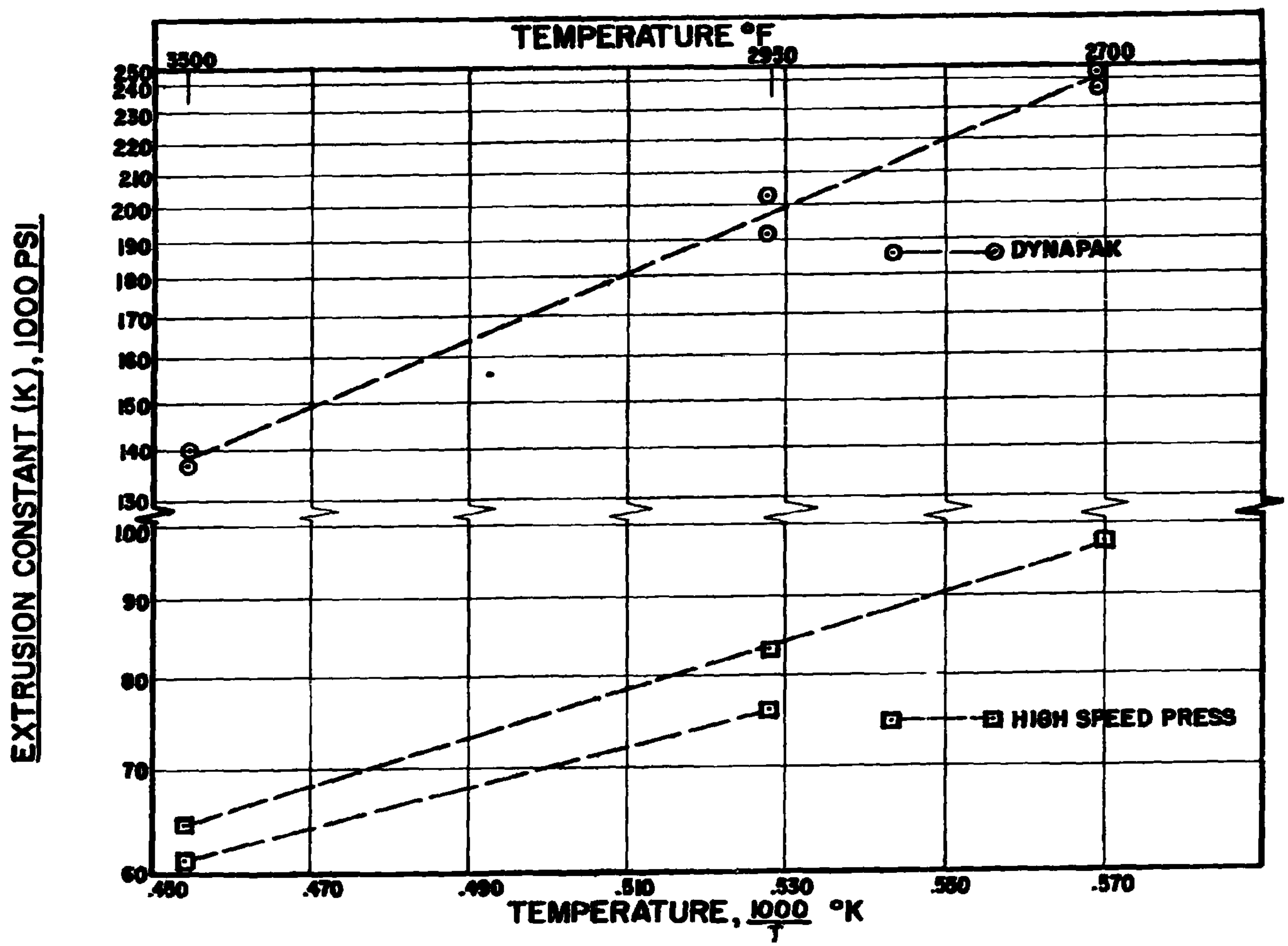


FIGURE 16 - Extrusion Constant (K) vs Temperature for the Dynapak & High Speed Press Extrusions of the Mo-25W-.1Zr Alloy

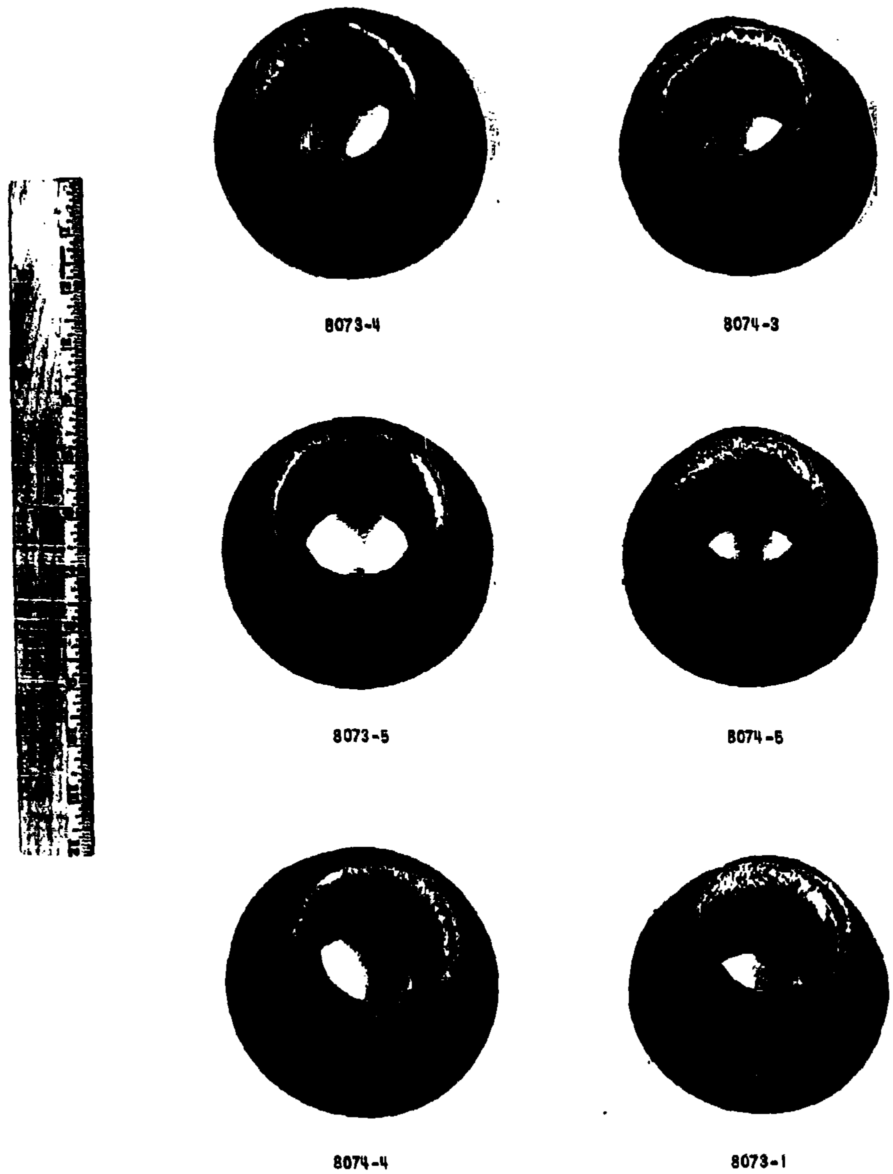


FIGURE 17 - High Speed Press Extrusion Dies After one Extrusion of the Billets Indicated

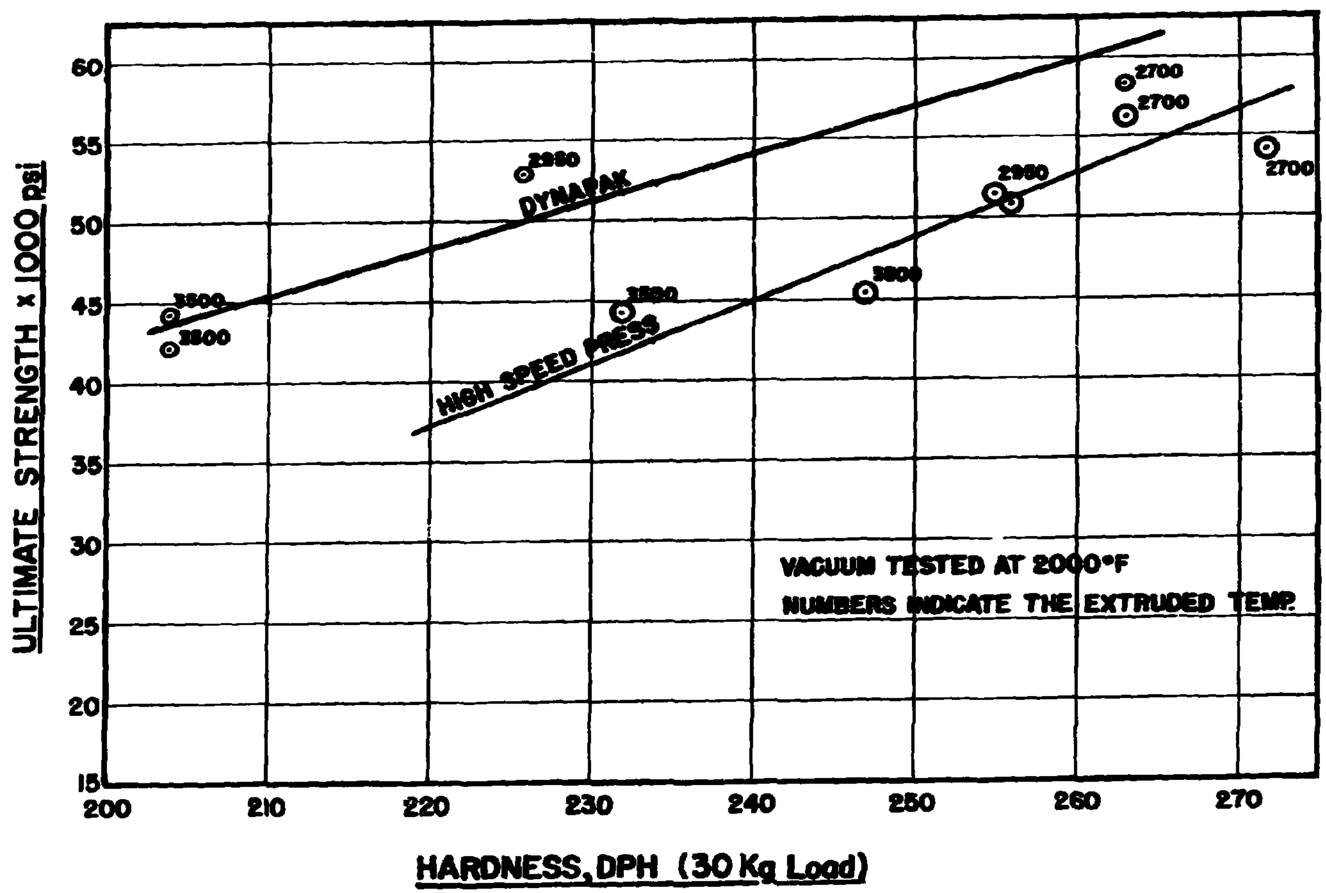


FIGURE 18 - High Temperature Strength vs Hardness for the Dynapak & High Speed Press Extruded Mo-25W-.1Zr Alloy

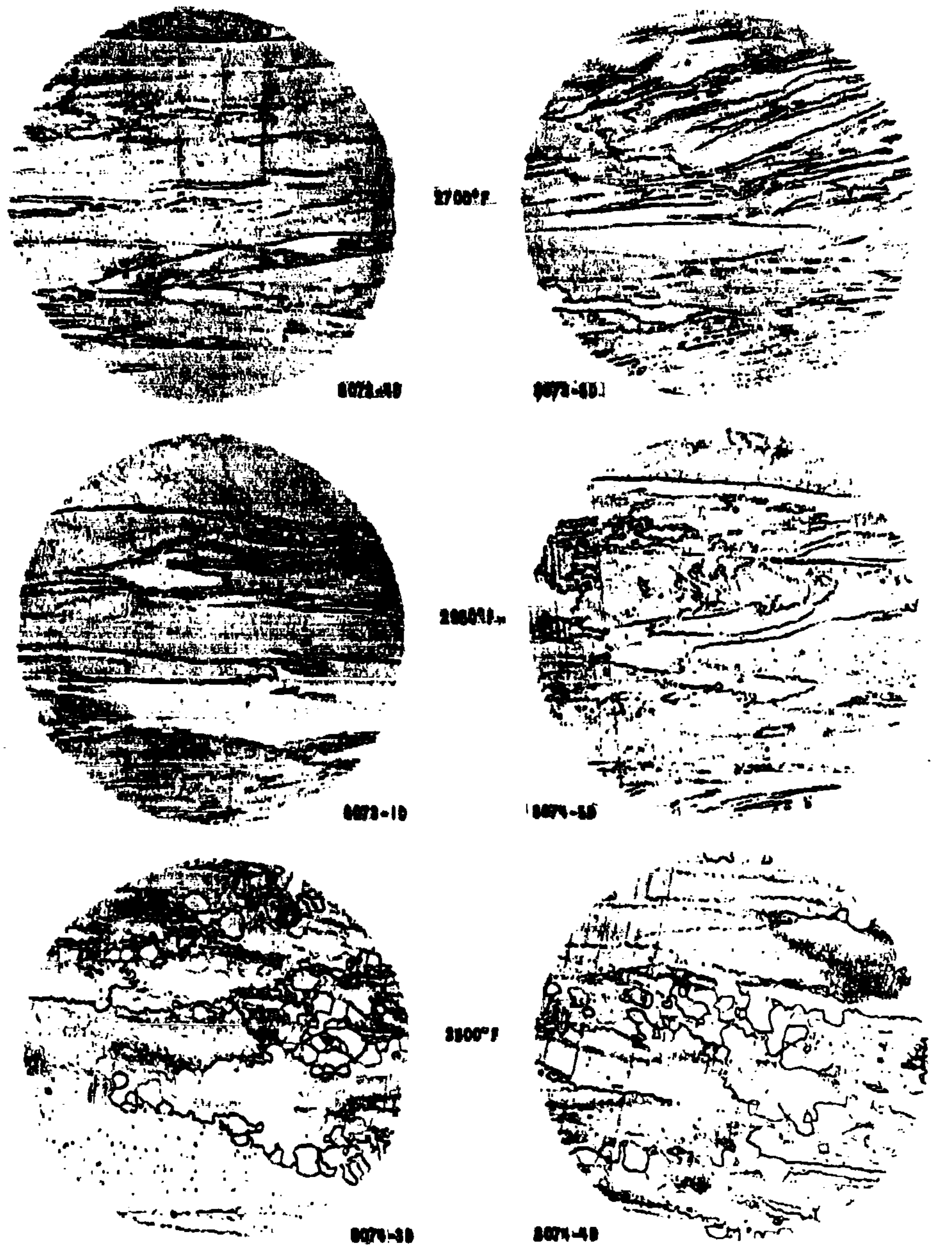
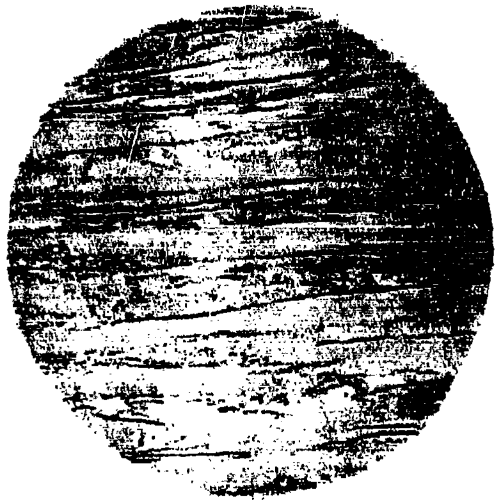
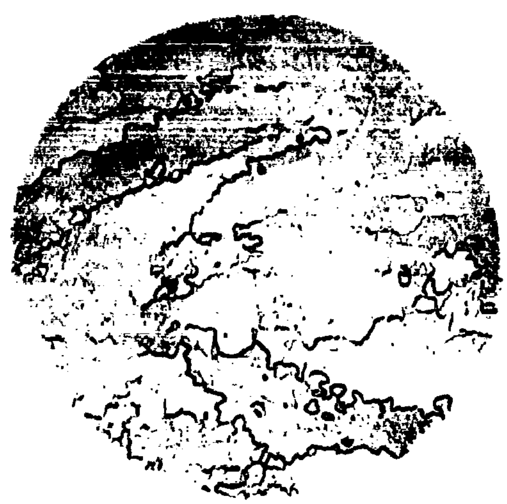


FIGURE 19 - Longitudinal Micrographs (100X) and Extruding Temperatures of High Speed Press Extruded Molybdenum Alloy Bars



8073-5H
A

8073-5H
B



8074-5D
C

FIGURE 20 - Longitudinal Micrographs of High Speed Press Extruded Molybdenum Alloy Bars

A. Tail End Near Surface - 100X
B. Tail End at Center of Cross Section - 100X
C. Same as Micrograph in Figure 14, but 500X

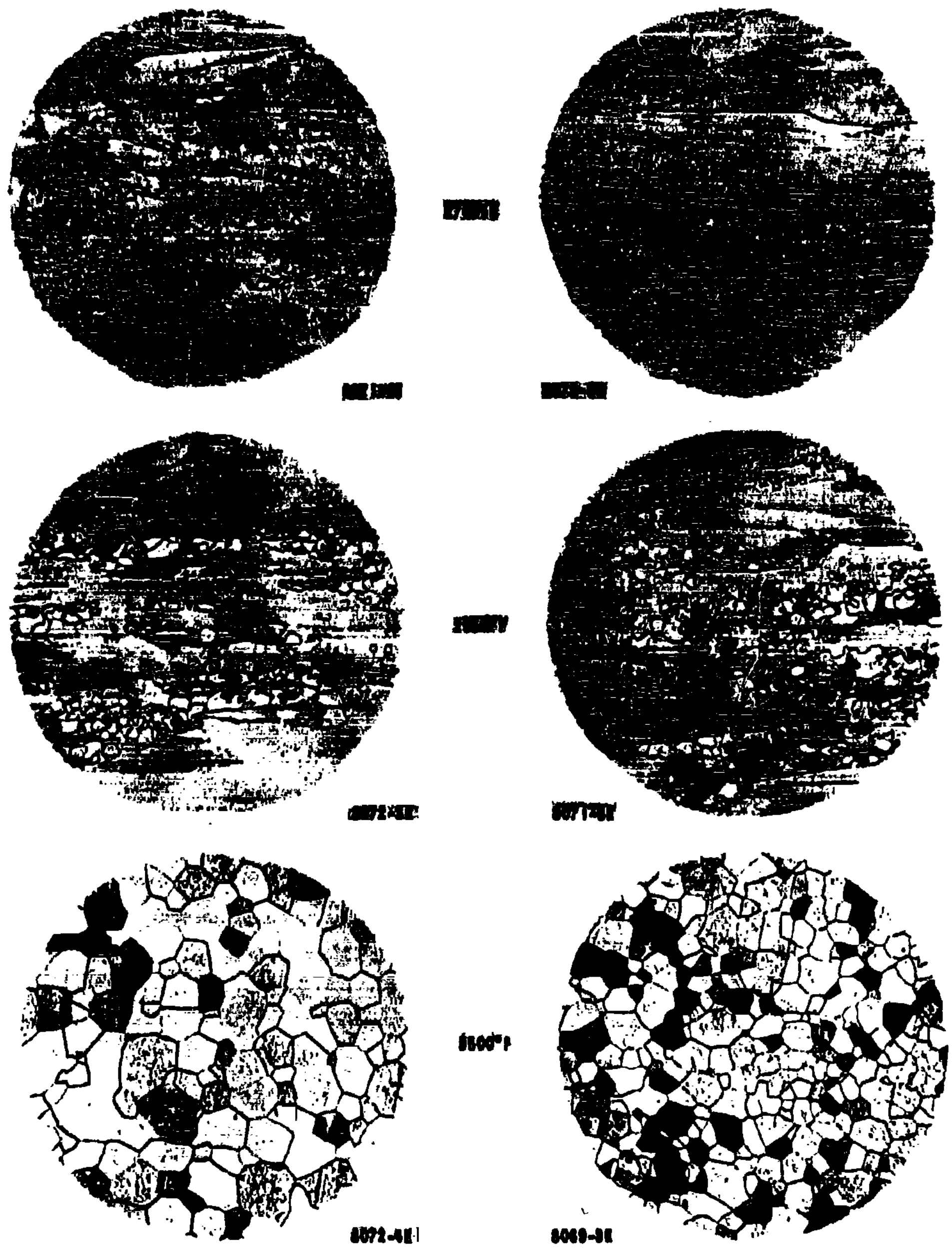
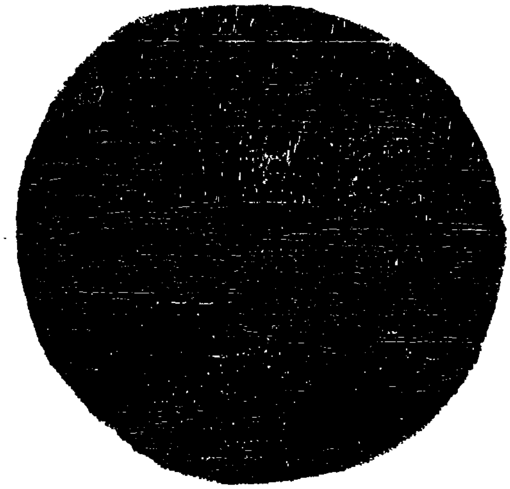
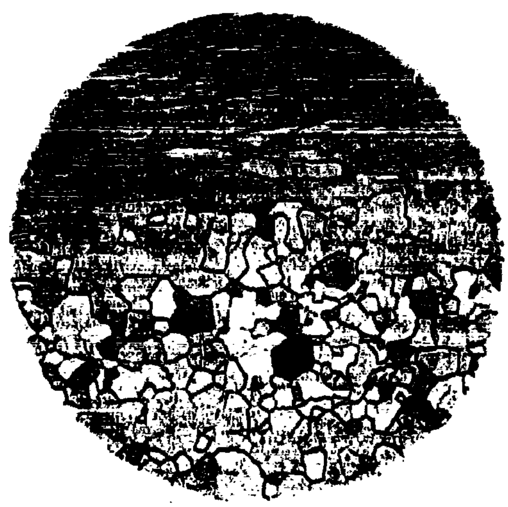


FIGURE 21 - Longitudinal Micrographs (100X) and Extruding Temperatures of Dynapak Extruded Molybdenum Alloy Bars



8071-5E
A



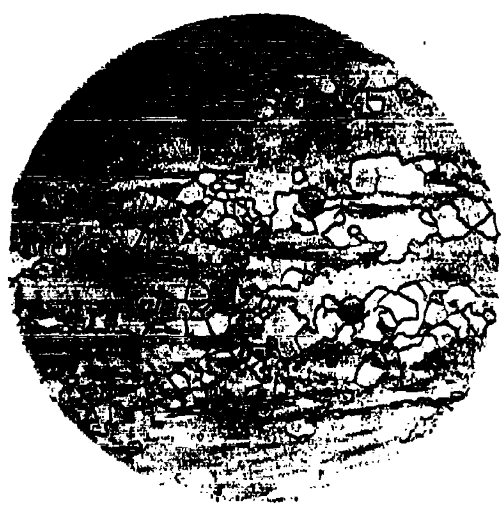
8069-3E
B

FIGURE 22 - Longitudinal Micrographs (100X) of Dynapak Extruded Molybdenum Alloy Bars

A. Area Near Surface of Extrusion from 2950°F
B. Area Near Surface of Extrusion from 3500°F

8073-5E29

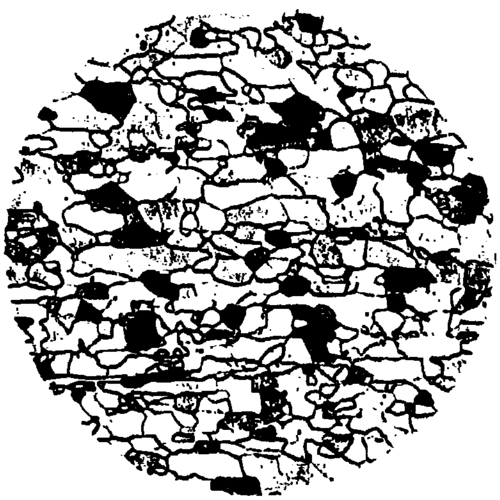
2700°F



8074-4E29

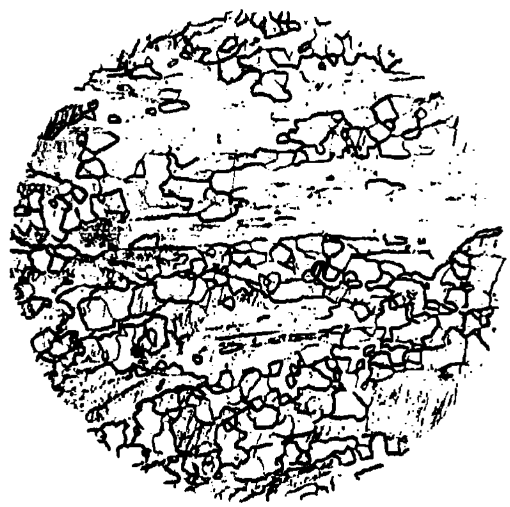
3500°F

FIGURE 23 - Longitudinal Micrographs (100X) and Extruding Temperatures of High Speed Press Extruded Molybdenum Alloy Bars Heat Treated for 1 Hour at 2900°F



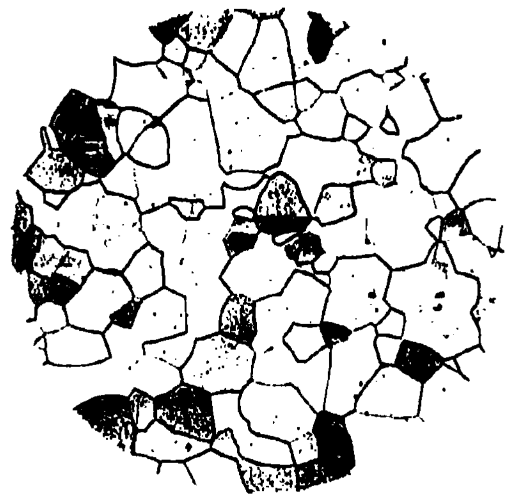
8071-6E29

2700°F



8071-5E29

2950°F



8072-4E29

3500°F

FIGURE 24 - Longitudinal Micrographs (100X) and Extruding Temperatures of Dynapak Extruded Molybdenum Alloy Bars Heat Treated for 1 Hour at 2900°F

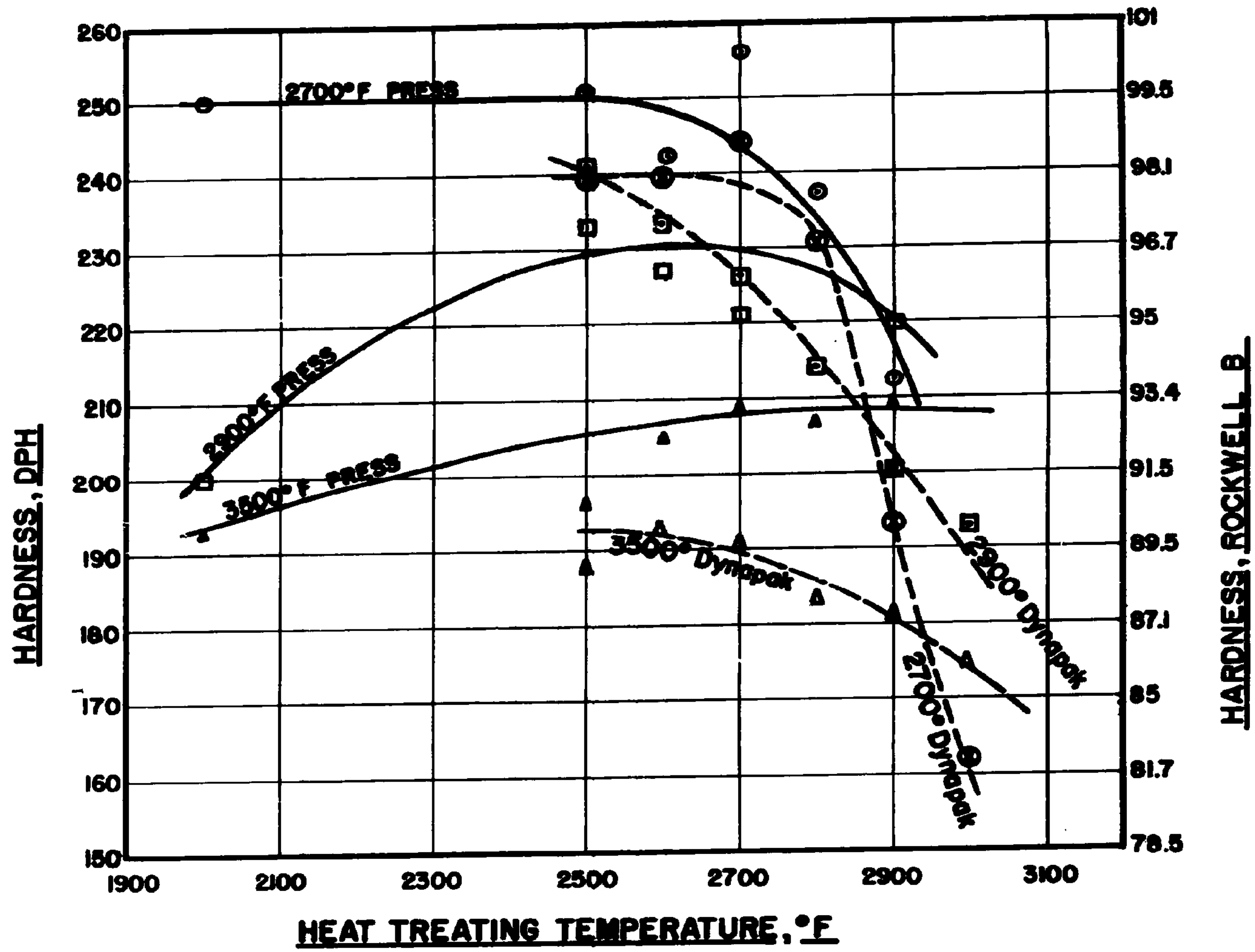


FIGURE 25 - Hardness vs Recrystallization Annealing Temperature for the Dynapak & High Speed Press Extruded Mo-25W-.1Zr Alloy

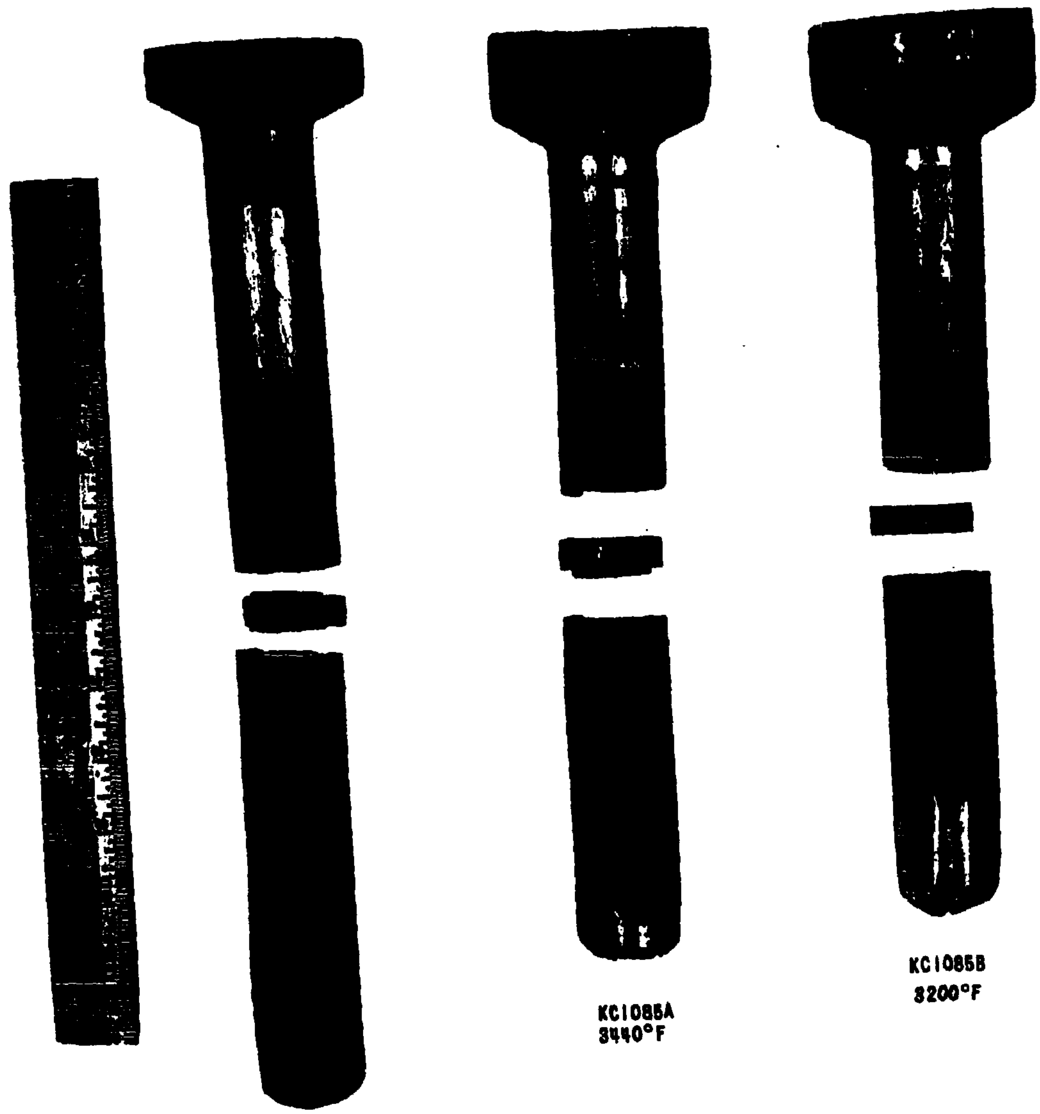
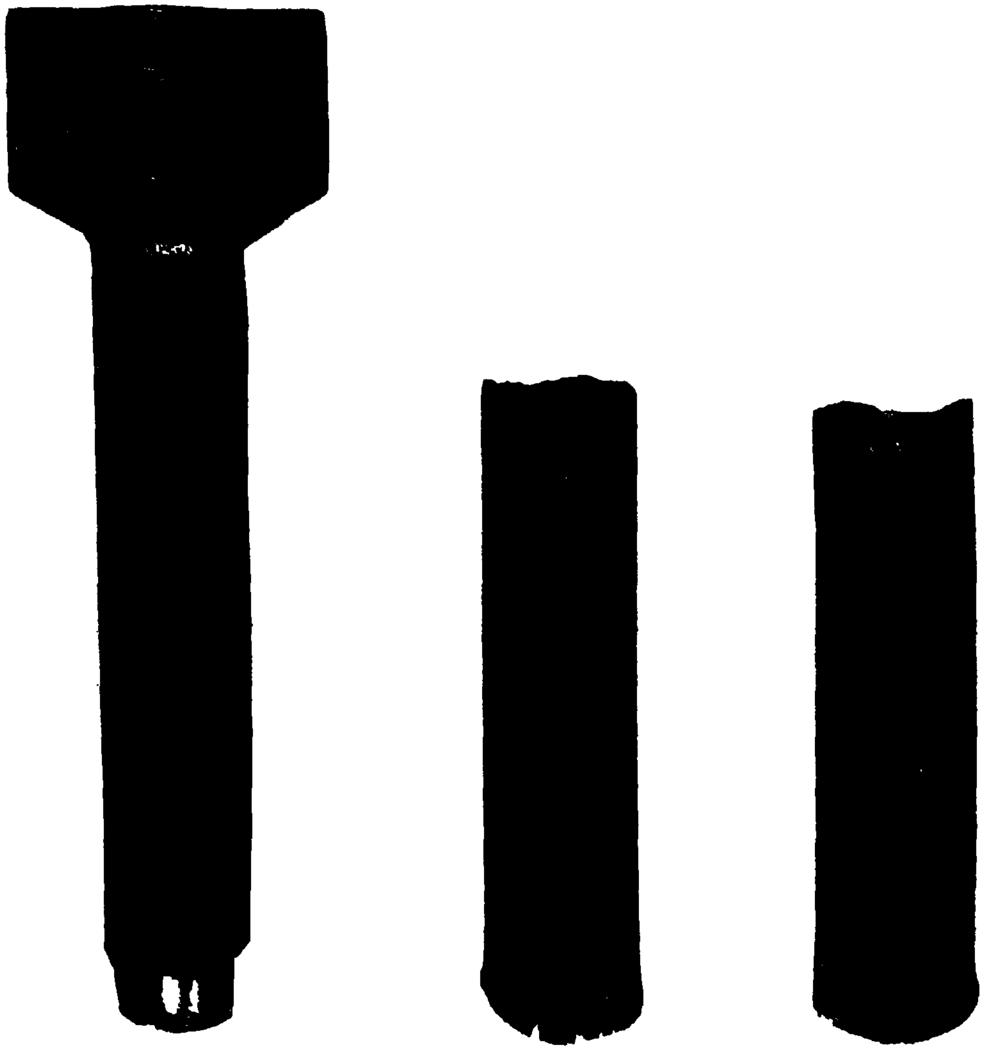


FIGURE 26 - Base Information Dynapak Extruded Tungsten Alloys Bars. As Extruded from the Indicated Temperatures



KC 1091A
3000°F

KC 1091B
2800°F

KC 1092A
2600°F

FIGURE 27 - Base Information Dynapak Extruded Tungsten Alloy Bars
As Estruded from the Indicated Temperatures

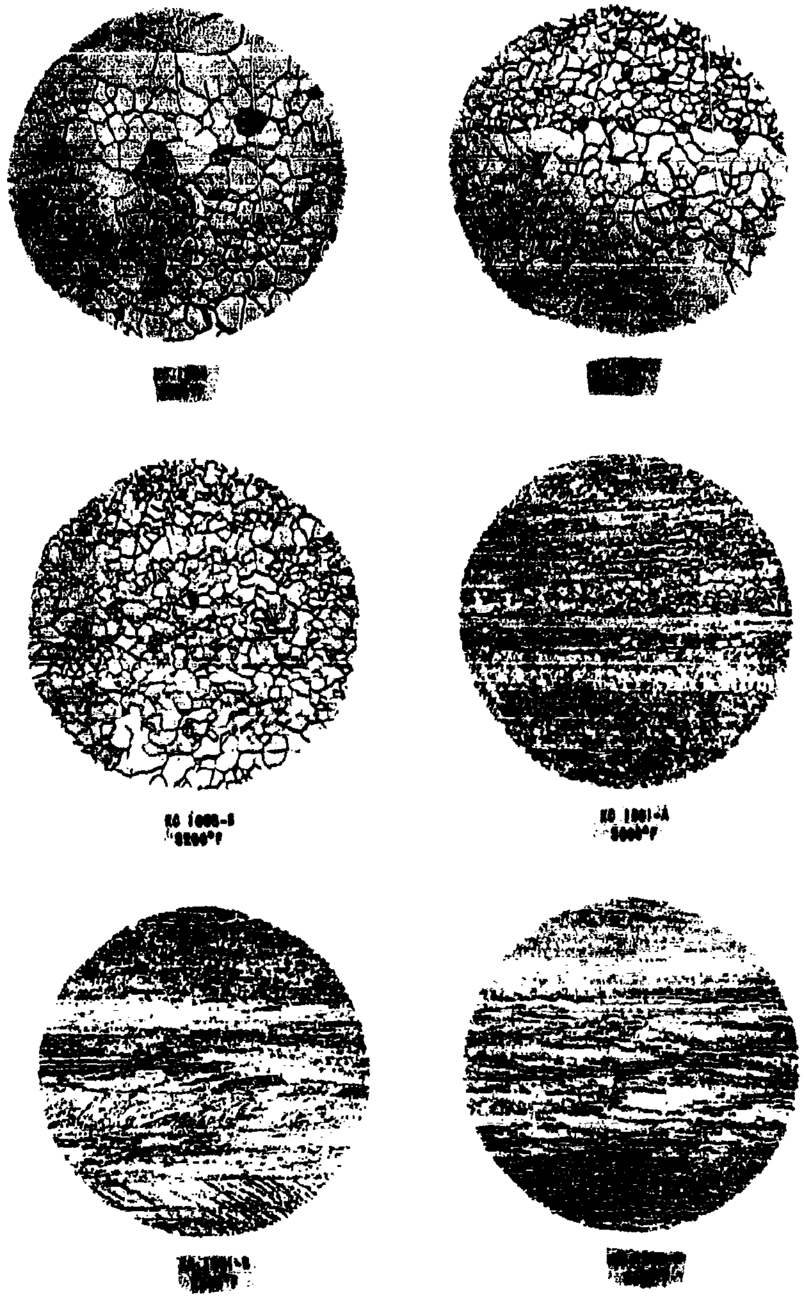


FIGURE 28 - Longitudinal Micrographs (100X) and Extruding Temperatures of Base-Information Dynapak Extruded Tungsten Alloy Bars

KC 1110A KC 1109B

FIGURE 29 - High Speed Press Extruded Tungsten Alloy Bars.
As Extruded from 2800°F

KC 1111A KC 1110B

FIGURE 30 - High Speed Press Extruded Tungsten Alloy Bars.
As Extruded from 3100°F

KC 1086A KC 1086B KC 1111B

FIGURE 31 - High Speed Press Extruded Tungsten Alloy Bars.
As Extruded from 3400°F

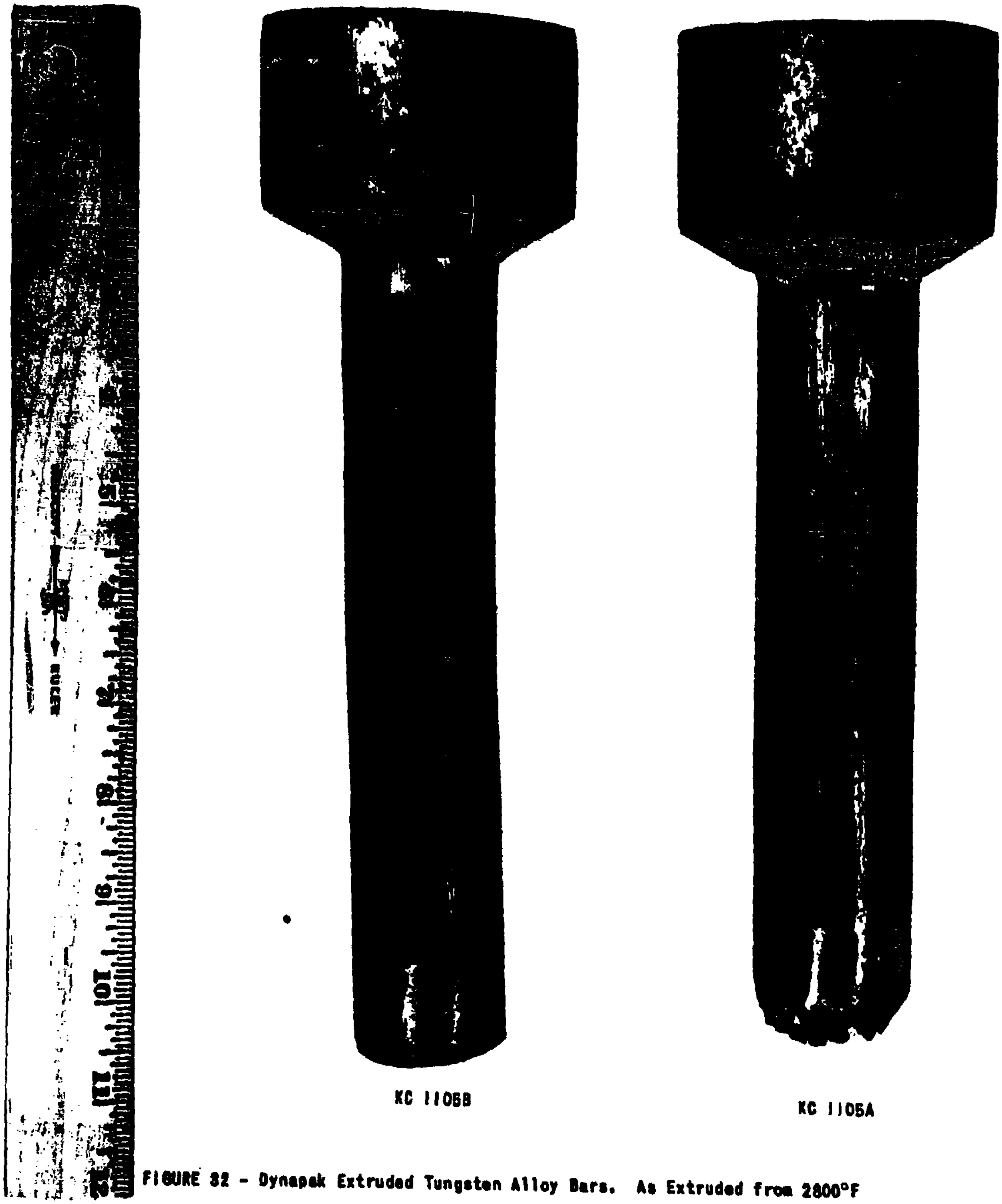
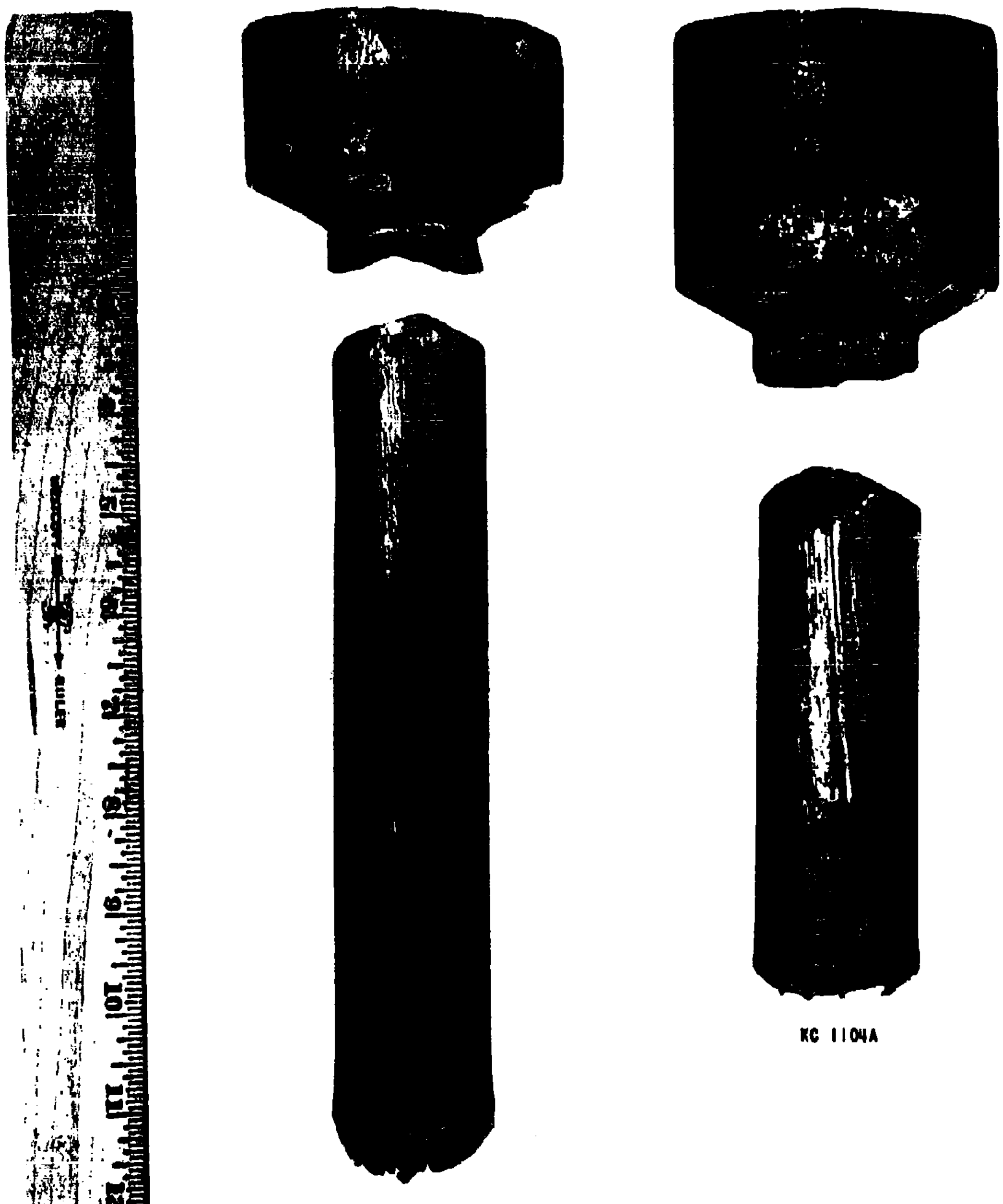


FIGURE 32 - Dynapak Extruded Tungsten Alloy Bars. As Extruded from 2800°F



KC 1092B

KC 1104A

FIGURE 33 - Dynapak Extruded Tungsten Alloy Bars. As Extruded from 3100°F

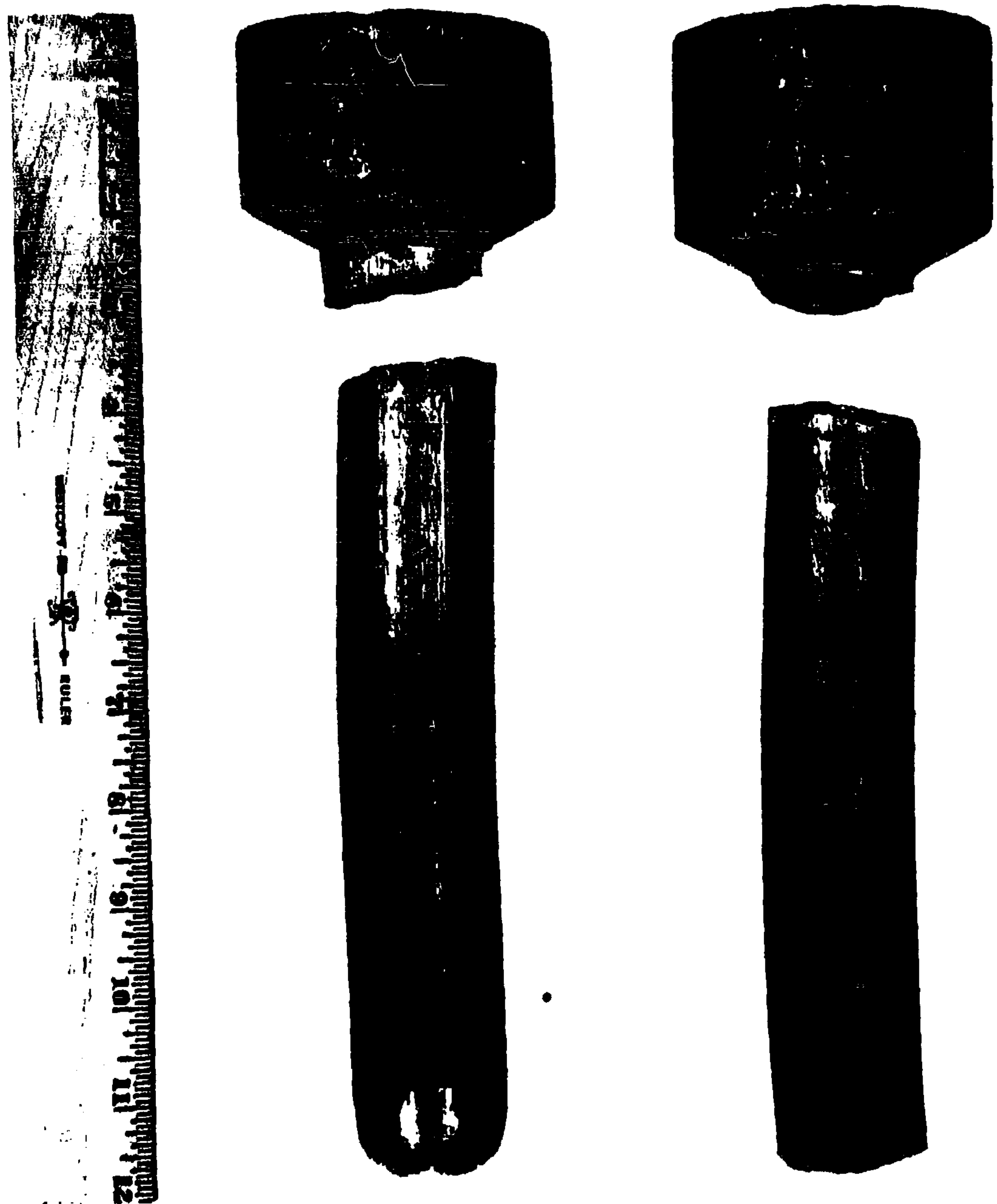


FIGURE 34 - Dynapak Extruded Tungsten Alloy Bars. As Extruded from 3400°F

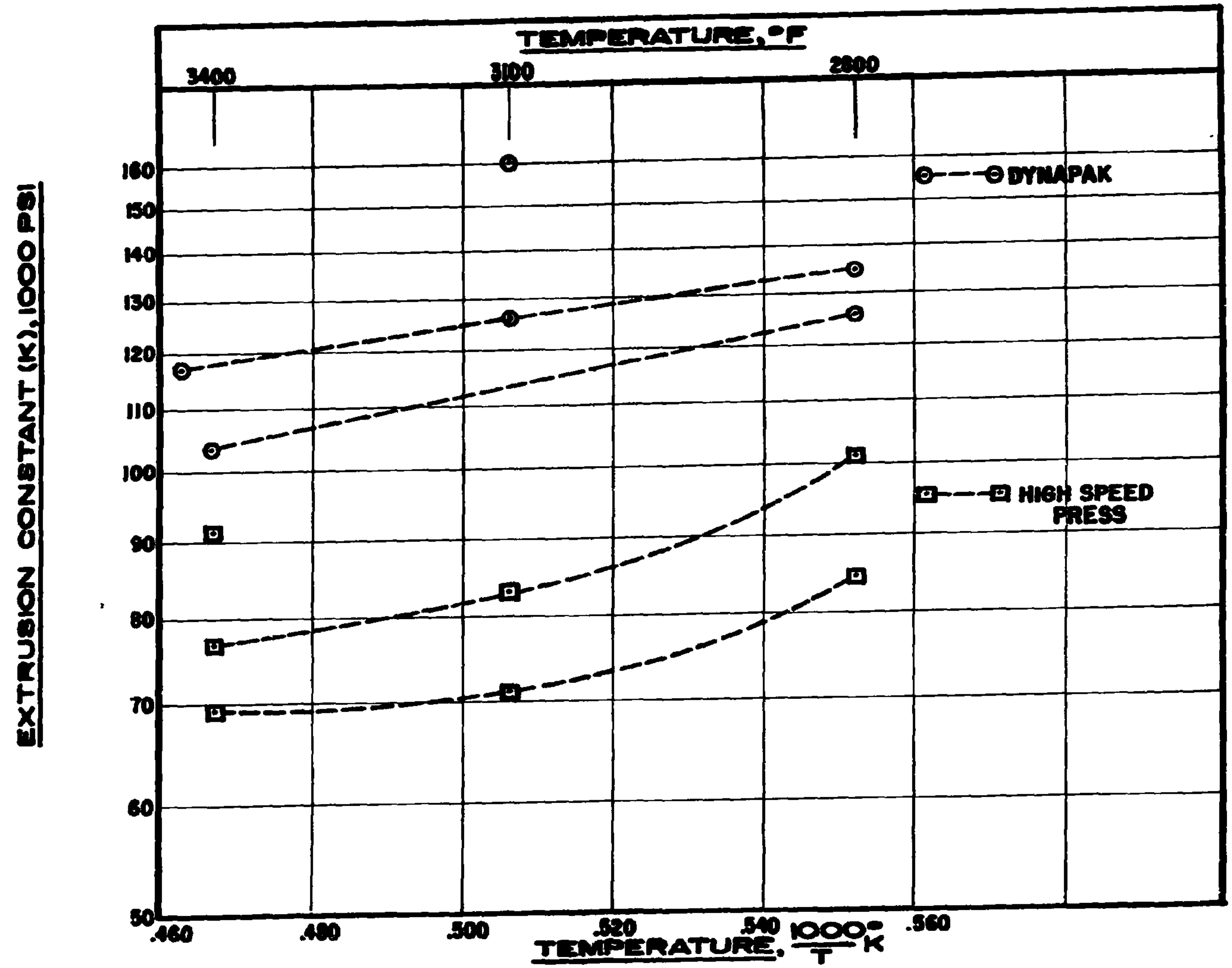
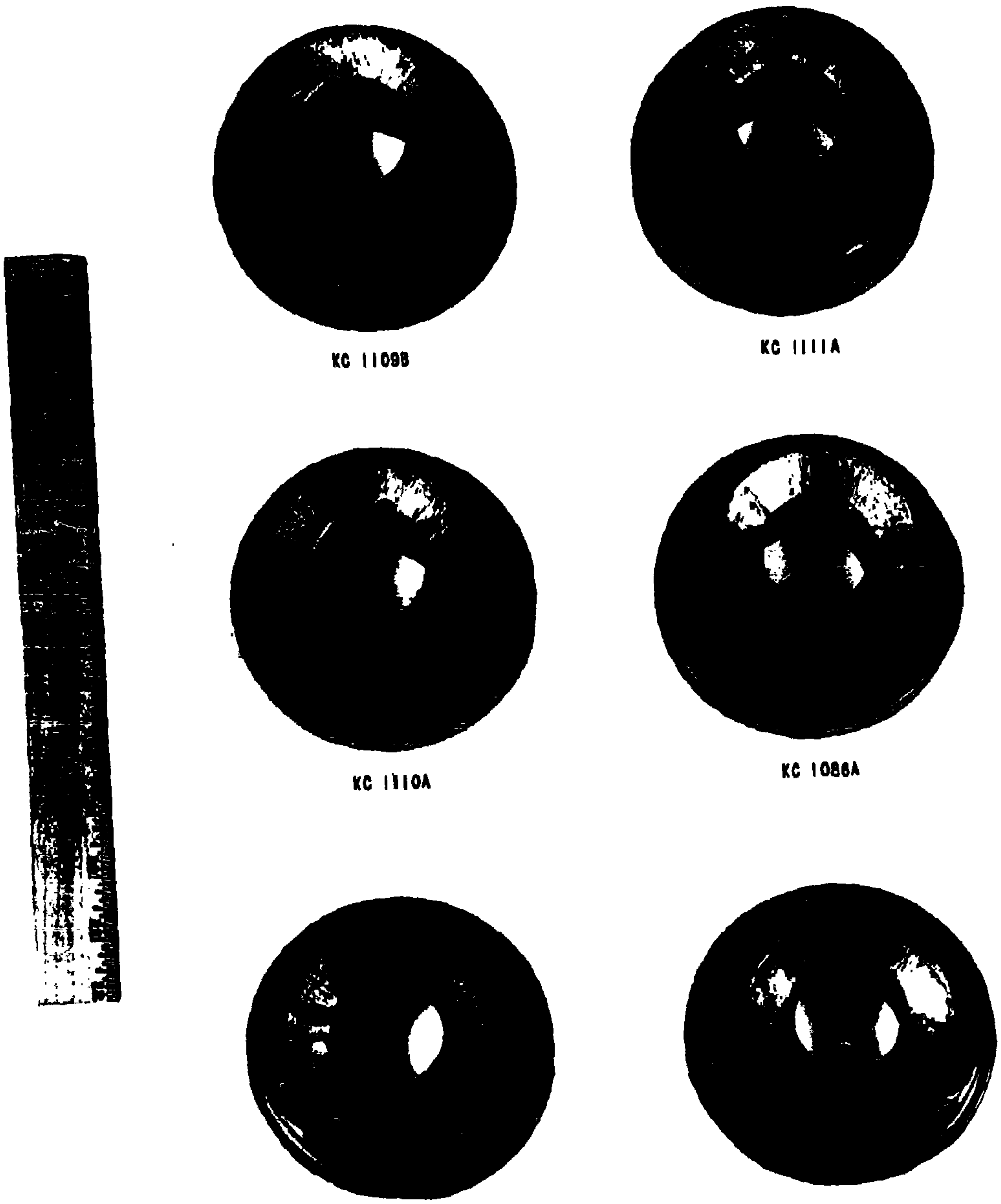


FIGURE 35 - Extrusion Constant (K) vs Temperature for the Dynapak & High Speed Press Extrusions of the Tungsten -- .6 Cb Alloy



KC 1109B KC 1111A

KC 1110A KC 1086A

KC 1110B KC 1086B

FIGURE 36 - High Speed Press Extrusion Dies After One Extrusion of the Tungsten Alloy Billet Indicated

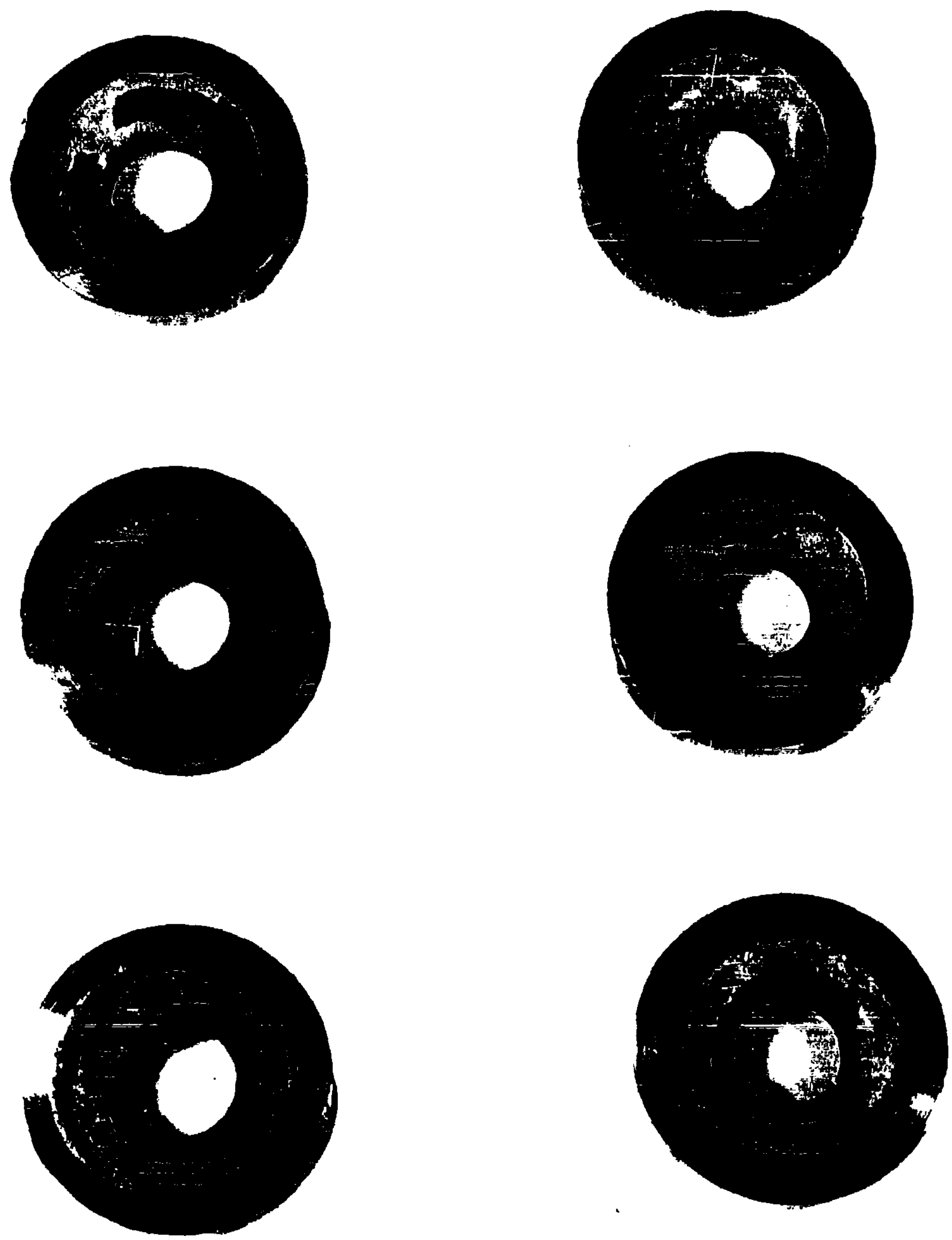


FIGURE 37 - Dynapak Extrusion Dies after One Extrusion of the Tungsten Alloy Billets Indicated

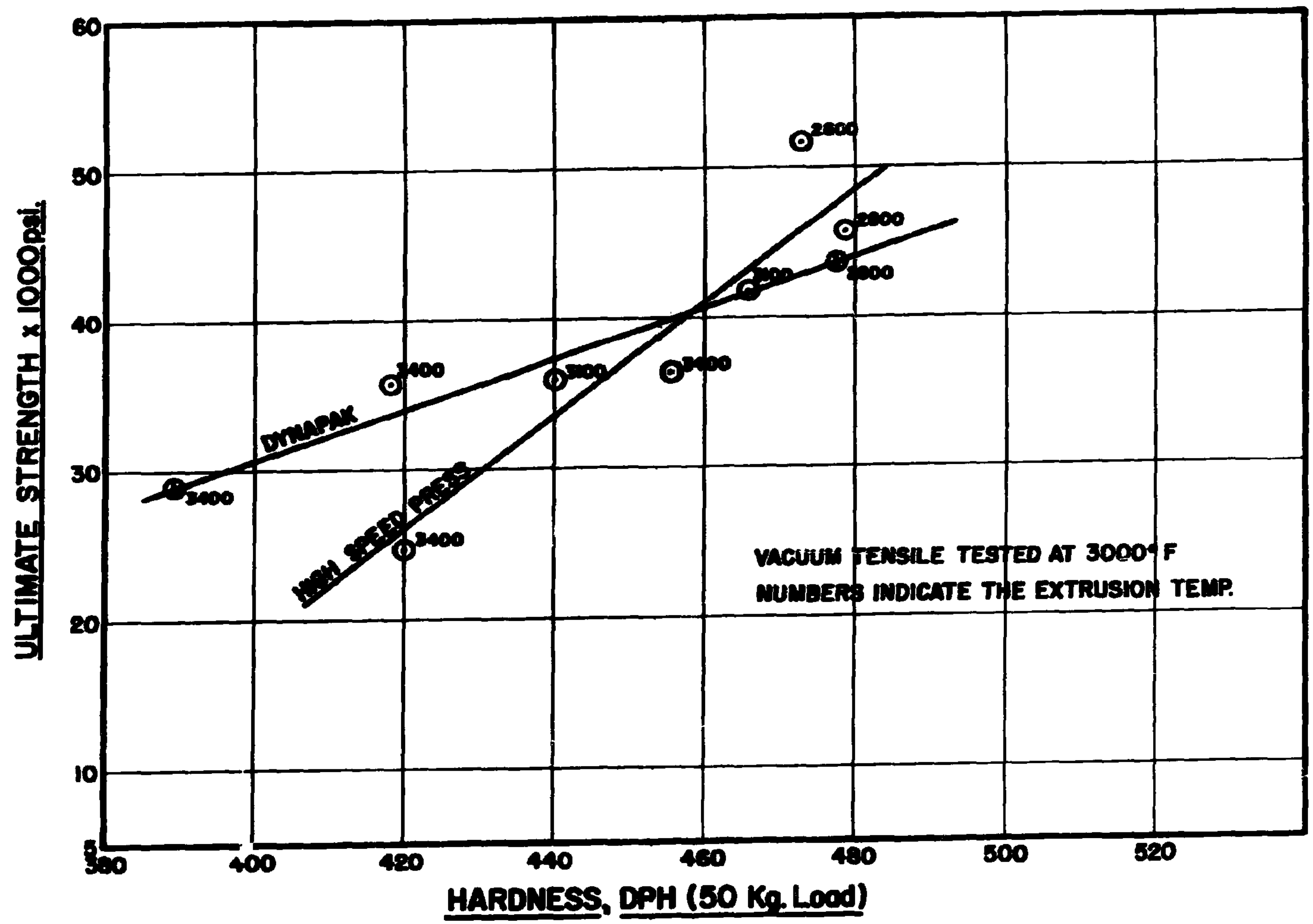


FIGURE 38 - High Temperature Tensile Strength vs Hardness for the Dynapak & High Speed Press Extruded Tungsten -- .6 Cb Alloy

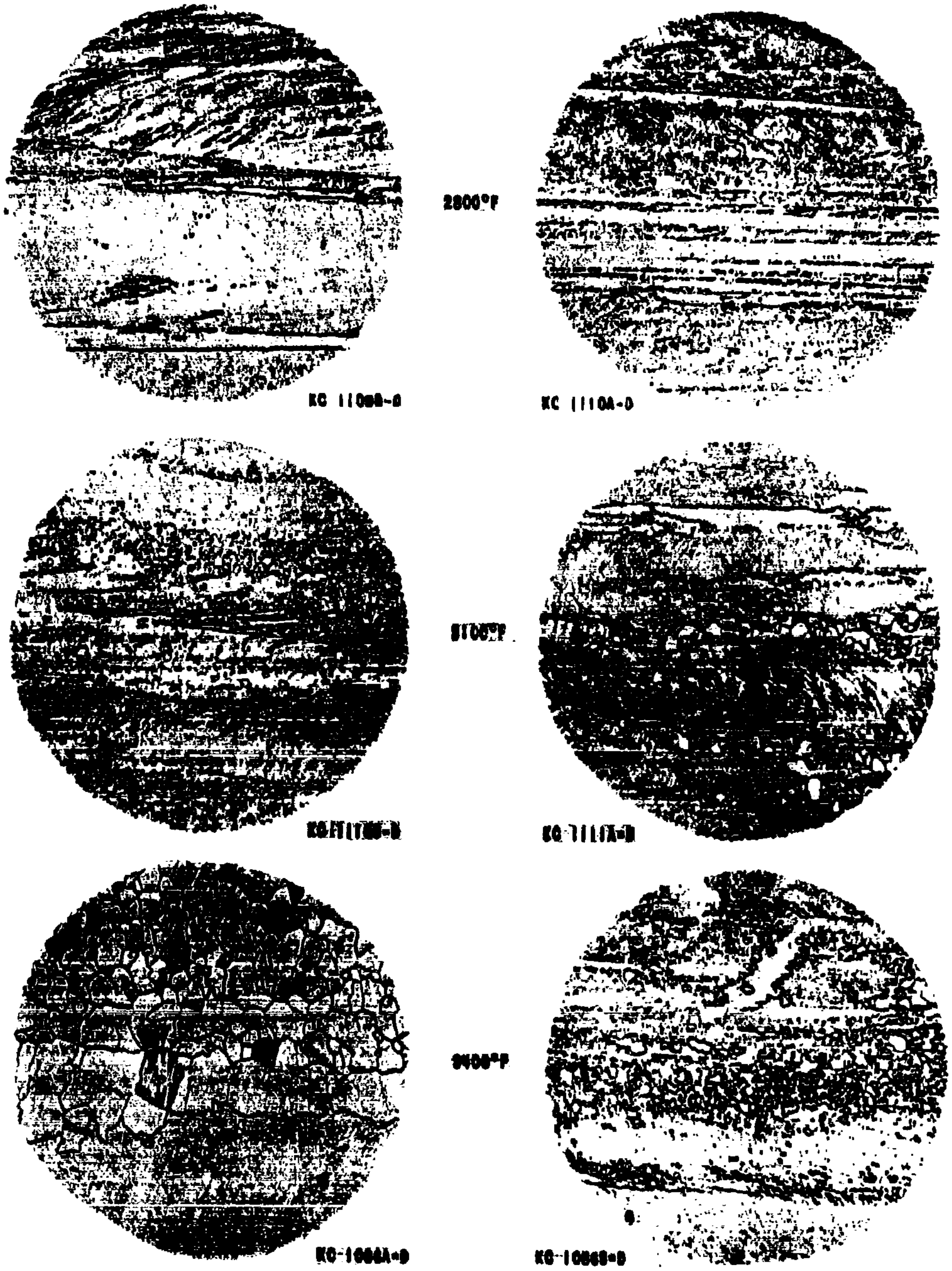
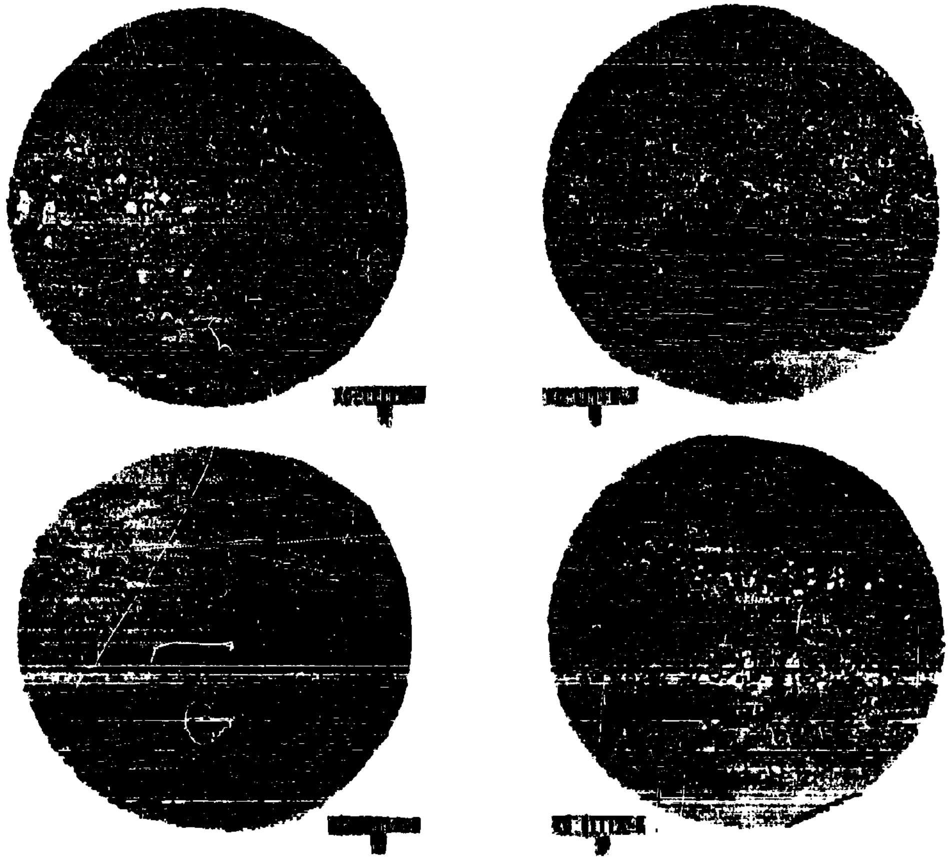
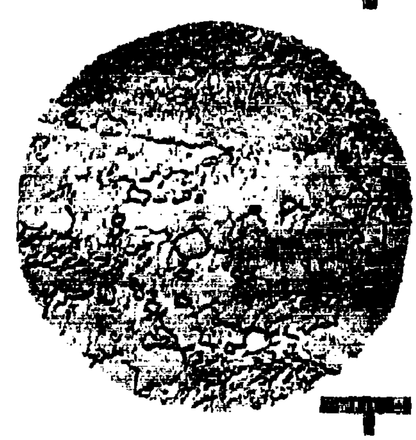


FIGURE 39 - Longitudinal Micrographs (100X) and Extruding Temperatures of High Speed Press Extruded Tungsten Alloy Bars





A - Center of Bar Extruded from 3400°F - 100X

B - Same as 'A' but Near Surface of Bar - 100X

C - Nose End at Center of Cross Section - 100X

D - Tail End at Center of Cross Section - 100X

E - Same as Micrograph in Figure 34, but 500X

FIGURE 40 - Longitudinal Micrographs of High Speed Press Extruded Tungsten Alloy Bars

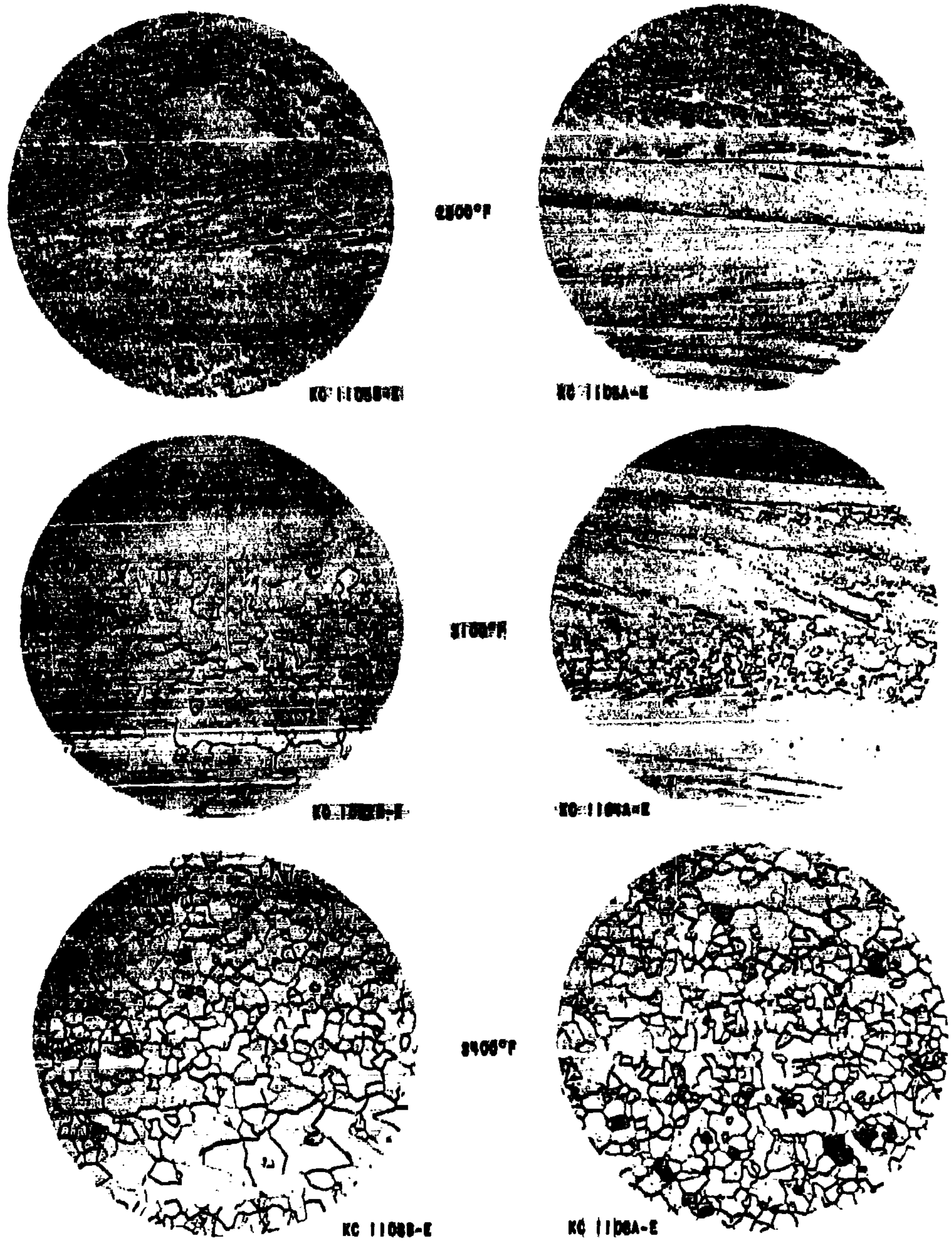
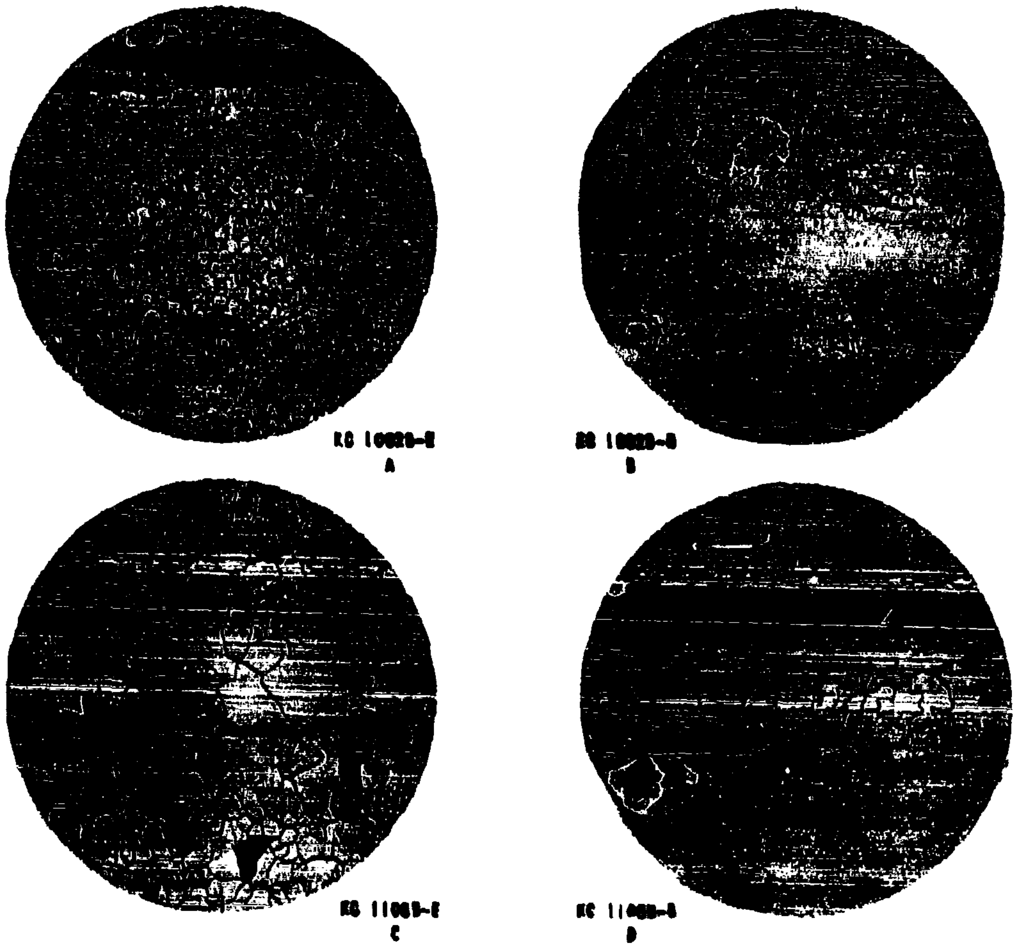


FIGURE 41 - Longitudinal Micrographs (100X) and Extruding Temperatures of Dynapak Extruded Tungsten Alloy Bars



A - Area Near Surface of Bar Extruded from 3100°F

B - Nose End at Center of Cross Section of Bar Extruded from 3100°F

C - Area Near Surface of Bar Extruded from 3400°F

D - Nose End at Center of Cross Section of Bar Extruded from 3400°F

FIGURE 42 - Longitudinal Micrographs 100X of Dynapak Extruded Tungsten Alloy Bars

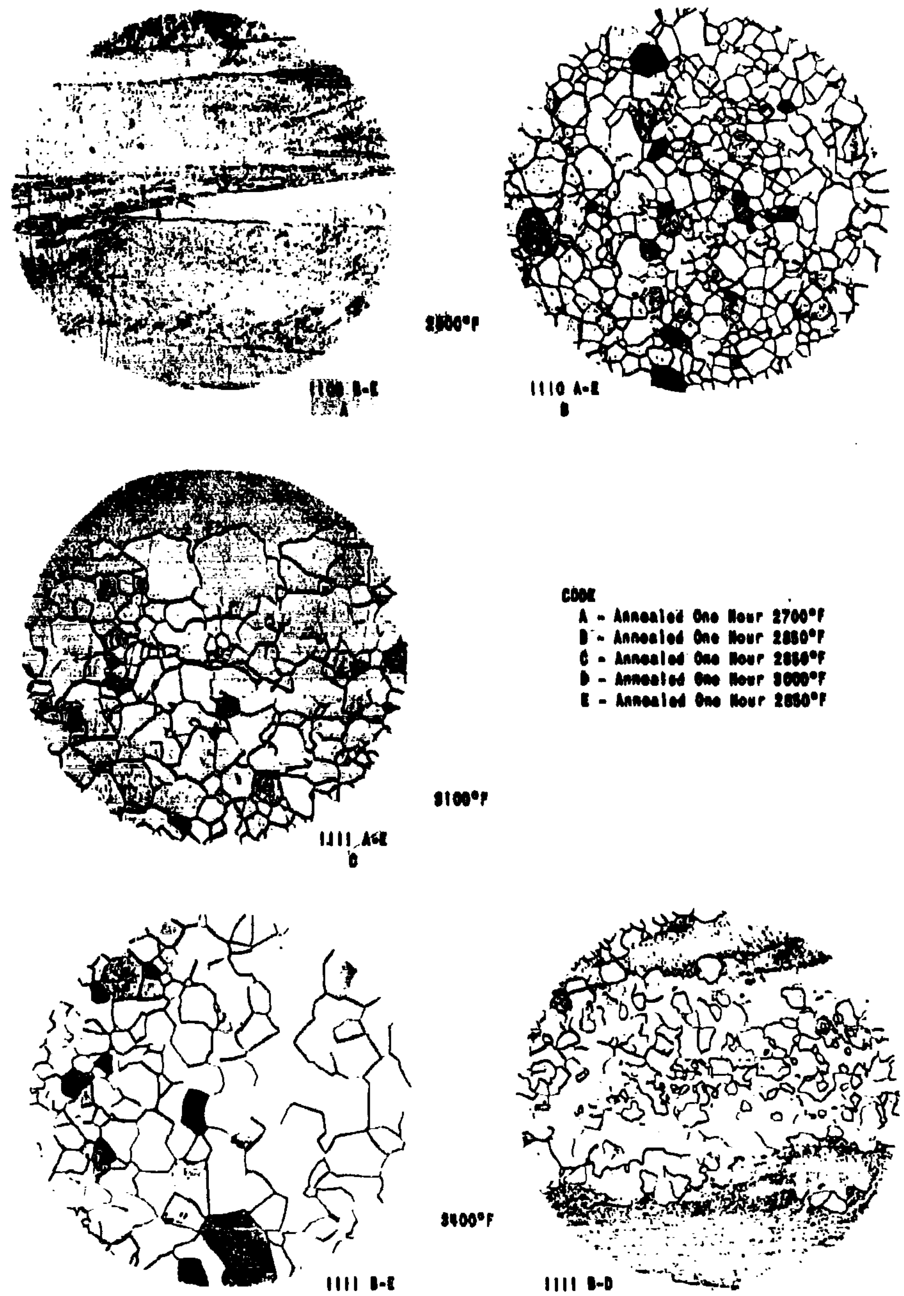


FIGURE 43 - Longitudinal Micrographs (100X) and Extruded Temperatures of High Speed Press Extruded Tungsten Alloy. Bars Heat Treated for One Hour

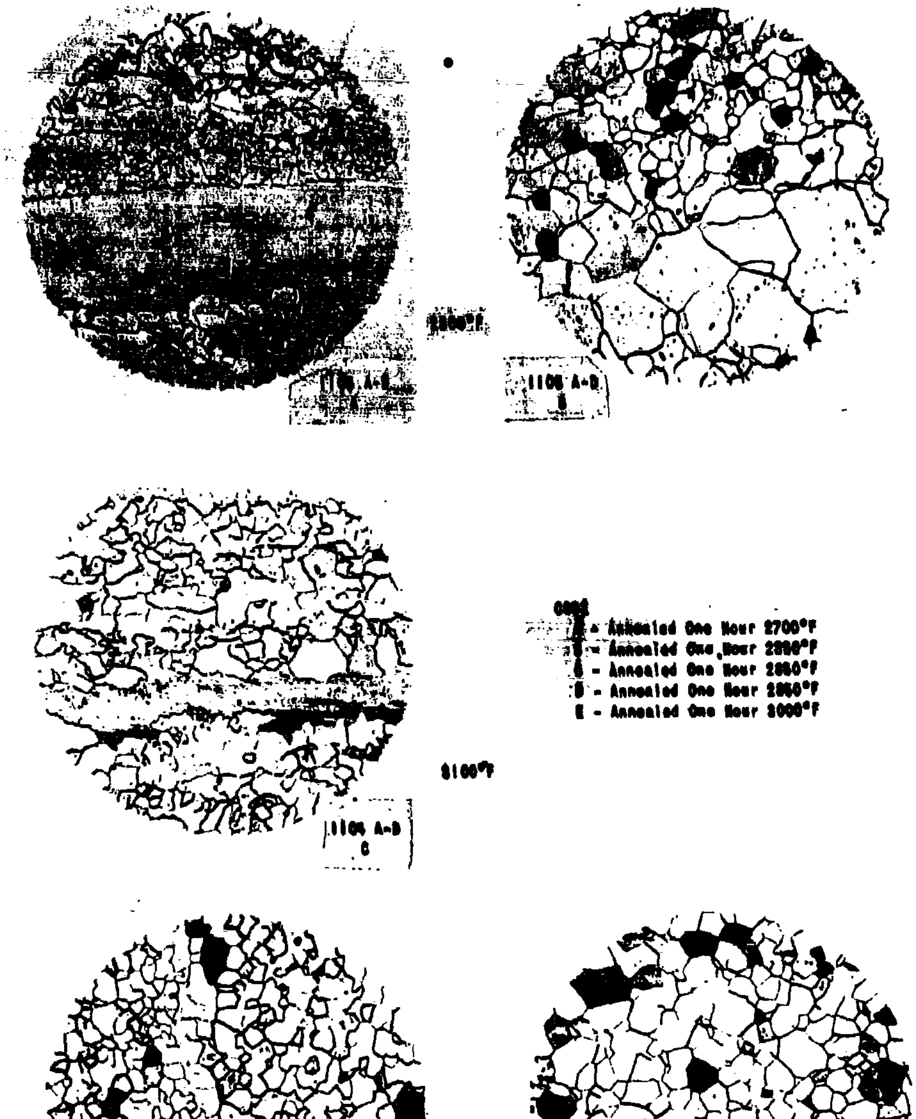


FIGURE 44 - Longitudinal Micrographs (100X) and Extruding Temperatures of Dynapak Extruded Tungsten Alloy. Bars Heat Treated for One Hour

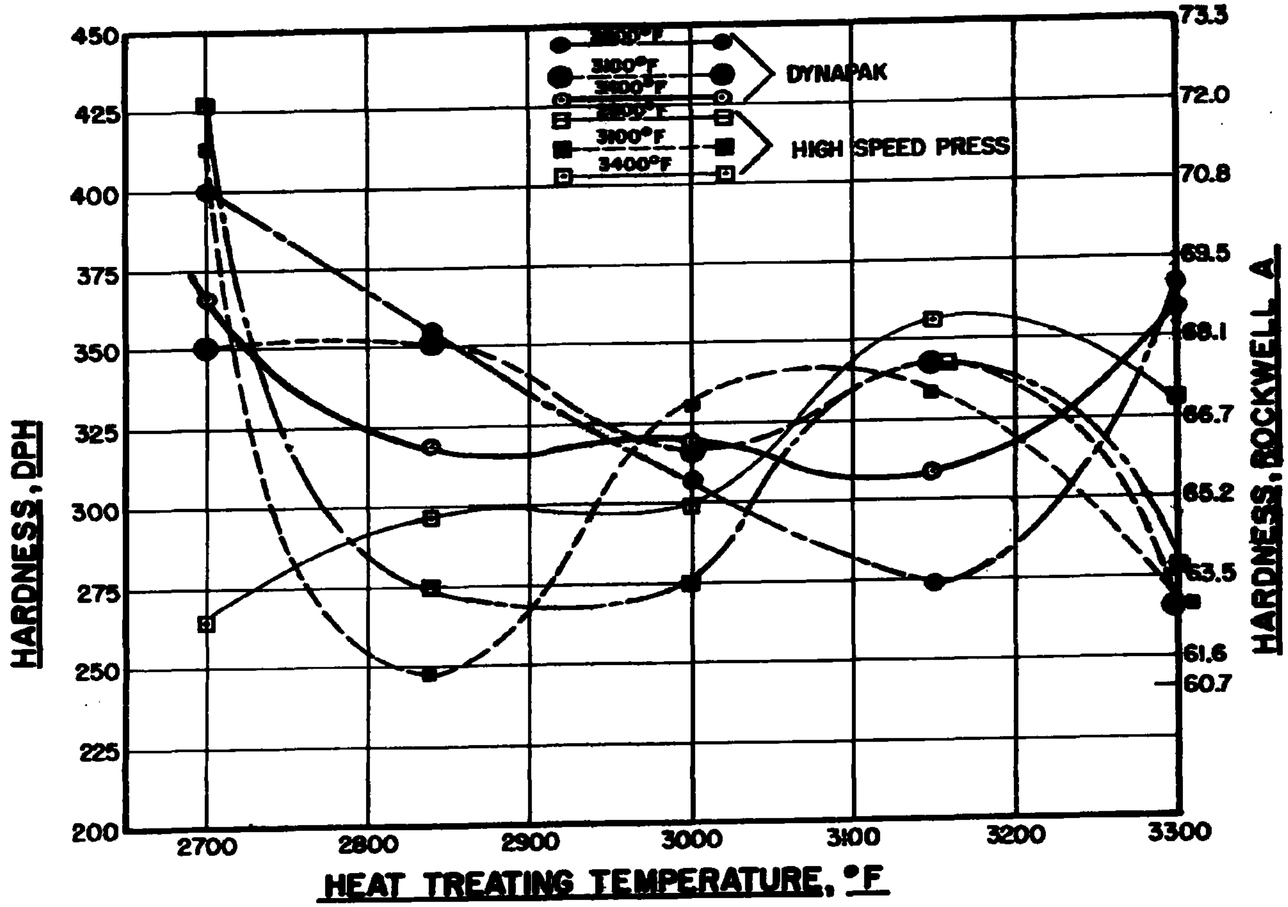


FIGURE 45 - Hardness vs Recrystallization Annealing Temperature for the Dynapak & High Speed Extruded Tungsten -- .6 Cb Alloy

TABLE 1

DIMENSION, CHEMISTRY AND HARDNESS OF ARC CAST Mo-25W - .1 Zr. ALLOY INGOTS

Ingot Number	Weight (Lbs.)	Length (In.)	W%	Zr%	C%	O_2 ppm	N_2 ppm (1)	DPH (2)
8067	77.6	20-1/2	25.11	.116	.004	2.5	1.5	
8067-3								171
8067-4								171
8067-5								171
8067-6								171
8068	74.8	19	24.79	.113	.004	9	3.5	
8068-3								178
8068-4								187
8068-5								180
8068-6								178
8069	77.5	20-1/2	24.57	.10	.002	10	2.5	
8069-3								185
8069-4								198
8069-5								185
8070	77	20-1/2	24.56	.11	.010	13	4	
8070-3								191
8070-4								179
8070-5								185
8070-6								185

TABLE 1 (continued)

DIMENSION, CHEMISTRY AND HARDNESS OF ARC CAST Mo-25W - .1 Zr. ALLOY INGOTS

Ingot Number	Weight (Lbs.)	Length (In.)	W%	Zr%	C%	O_2 ppm	N_2 ppm(1)	DPH(2)
8071	70	18-3/4	24.84	.129	.015	10	3	
8071-1								183
8071-5								180
8071-6								180
8072	---	21-3/4	25.00	.102	.018	8	3	
8072-3								180
8072-4								180
8072-5								180
8073	---	21-1/4	24.90	.07	.008	5	2	
8073-1								191
8073-4								183
8073-5								178
8074	80.4	21-3/4	25.0	.07	.007	9	2.5	
8074-3								183
8074-4								178
8074-5								178

(1) These elements were analyzed by the vacuum extraction technique. The precision of these measurements is determined by the blank-off pressure obtained just prior to heating the sample. With the normally obtained low blank-off pressure, a precision of ± 3 ppm or less is obtained.

(2) These numbers are the average of two readings taken at the top end of the billets. These readings were taken using BHN, 10-mm standard ball and 1000-kg load and converted by using the Steel Hardness Conversion Tables.

TABLE 2

DIMENSIONS, CHEMISTRY AND HARDNESS OF ARC CAST W-.6Cb ALLOY INGOTS

Ingot Number	Weight (lbs.)	Length (In.)	Cb%	Mo%	C%	O_2 ppm	N_2 ppm (1)	DPH Edge Top/Bottom	DPH Mid-Radius Top/Bottom (2)
1084	20.17	4-3/16	.54	.0015	.0040	10	2	----------	----------
1085-A	18.80	3-7/8	.55	.0030	.0043	7	4	----------	----------
1085-B	18.87	3-7/8						----------	----------
1086-A	19.42	4	.55	.0015	.0017	4	3	317/317 (3)	333/333 (3)
1086-B	18.86	3-15/16						333/333	333/333
1090	19.40	4	.60	.0045	.0030	8	2	333/302	333/317
1091-A	19.10	3-15/16	.57	.0028	.0031	13	2	333/333	333/333
1091-B	19.80	3-15/16						317/333	333/333
1092-A	18.65	3-7/8	.56	.0019	.0025	20	28	317/333	333/333
1092-B	18.84	3-7/8						333/333	333/333
1104-A	20.55	4-1/4	.54	.0045	.0033	9	17	357/322 (4)	339/339 (4)
1104-B	20.15	4-3/16						305/339	313/349
1105-A	20.40	4-1/4	.54	.0028	.0027	8	20	275/330	298/357
1105-B	20.40	4-1/4						357/339	349/349
1108-A	20.40	4-1/4	.60	.0026	.0011	8	11	339/330	349/349
1108-B	20.20	4-1/4						269/290	305/330

TABLE 2 (continued)

DIMENSIONS, CHEMISTRY AND HARDNESS OF ARC CAST W-.6Cb ALLOY INGOTS

Ingot Number	Weight (Lbs.)	Length (In.)	Cb%	Mo%	C%	O_2 ppm	N_2 ppm[1]	DPH Edge Top/Bottom	DPH Mid-Radius Top/Bottom
1109-A	20.50	4-1/4	.58	.0018	.0011	7	25	339/330	330/339
1109-B	20.30	4-1/4						349/339	322/349
1110-A	20.30	4-3/16	.60	.0016	.0017	14	26	357/330	349/339
1110-B	20.35	4-1/4						305/313	384/349
1111-A	20.45	4-1/4	.54	.0020	.0014	18	23	330/330	349/349
1111-B	20.55	4-1/4						330/330	339/349

(1) In all the ingots, the following elements were also detected by spectrographic analysis:

H_2	2 ppm	Mn	.0010%
Al	.0010%	Si	.0020%
Cu	.0001%	Fe	.0025%
Mg	.0001%	Co	.0005%
Sn	.0020%	Cr	.0010%
Ti	.0001%	Ni	.0001%

(2) These readings were not taken.

(3) These readings were taken using BHN, 10-mm standard ball and 1000-kg. load and converted by using the Steel Hardness Conversion Tables.

(4) These readings were converted from Rockwell Hardness number A scale (60-kg. load, Diamond Cone Penetrator) by using the Steel Hardness Conversion Tables.

TABLE 3

EXTRUSION PARAMETERS USED FOR DYNAPAK EXTRUDING THE Mo-25W-.1Zr ALLOY

Billet Number	BILLET Diameter (Inches)	BILLET Length (Inches)	BILLET Weight (Lbs.)	BILLET Temp. (°F)	Transfer Time (Sec.)	Fire Pressure (psi)	Ext. Ratio	DIE Condition	DIE Bore (Inches)
Base Information									
8067-3	2-7/8	2-15/16	7.72	2915	11	1500	4:1	New	1.500
8067-4	2-7/8	2-15/16	7.81	2840	14	1500	4:1	New	1.500
8070-3	2-7/8	3	7.9	3450	10	1500	4:1	New	1.500
8070-4	2-7/8	2-15/16	7.7	3460	9	1500	4:1	New	1.500
8070-6	2-7/8	3	7.9	2700	7	1800	4:1	New	1.500
8069-4	2-7/8	3-3/4	10.05	2985	9	1800	4:1	New	1.500
Program Runs									
8069-3	2-7/8	3-11/16	9.82	3495	12	1800	4:1	Reconditioned	1.5295
8071-5	2-7/8	3-15/16	10.5	2955	9	1800	4:1	Reconditioned	1.506
8071-6	2-7/8	4-1/16	10.74	2705	9	1800	3.9:1	Reconditioned	1.519
8072-3	2-7/8	3-29/32	10.43	2950	8	1800	3.87:1	Reconditioned	1.526
8072-4	2-7/8	3-15/16	10.42	3500	11	1800	4:1	New	1.500
8072-5	2-7/8	3-3/4	10.5	2700	8	2000	3.86:1	Reconditioned	1.529

Lubrication

Billet: 7052 - 100 mesh glass manufactured by Corning Glass.
Die and Container: Aquadag - colloidal graphite in water manufactured by Acheson.

TABLE 4

EXTRUSION PARAMETERS USED FOR HIGH SPEED PRESS EXTRUDING THE Mo-25W-1Zr ALLOY

Billet Number	BILLET Diameter (Inches)	Length (Inches)	Weight (Lbs.)	Transfer Temp. (°F)	Time (Sec.)	Ext. Ratio	DIE Condition	Bore (Inches)
Base Information								
8068-3	3	2-13/16	8.03	2670	10	4:1	New	1.562
Program Runs								
8074-4	3	4-3/8	12.77	3500	12	4:1	New	1.562
8074-3	3	4-9/32	12.4	3500	10	4:1	New	1.562
8074-5	3	4-5/16	12.41	2950	11	4:1	New	1.562
8073-1	3	4-1/8	11.82	2950	12	4:1	New	1.562
8073-4	3	3-3/4	10.85	2700	11	4:1	New	1.562
8073-5	3	3-25/32	10.99	2700	11	3.5:1	Used	1.658

LUBRICATION

Billet: 7052-100 mesh glass manufactured by Corning Glass.
For both base - information and program runs.

Die: Base information - graphite and grease.
Program runs - Aquadag (colloidal graphite in water manufactured by Acheson)

Container: Graphite and grease.
For both base - information and program runs.

Fiske's lubricant No. 604 manufactured by Fiske Brothers Refining Co.

TABLE 5

EXTRUSION PARAMETERS USED FOR DYNAPAK EXTRUDING THE W-.6Cb ALLOY

Billet Number	BILLET Diameter (Inches)	BILLET Length (Inches)	BILLET Weight (Lbs.)	BILLET Temp. (°F.)	Transfer Time (Sec.)	Fire Pressure (psi)	Ext. Ratio	LUBRICATION Billet	DIE[3] Bore (Inches)
Base Information									
KC 1084	2.925	4-3/16	19.14	3900[1]	7	1500	4:1	7810[2]	1.446
KC 1085-A	2.925	3-7/8	17.98	3440	12	1500	4:1	7810	1.488
KC 1085-B	2.925	3-7/8	17.95	3200	8	1625	4:1	7810	1.495
KC 1091-A	2.925	3-15/16	18.15	3000	12	1600	4:1	7810	1.500
KC 1091-B	2.925	3-15/16	18.10	2800	12	1600	4:1	7810	1.500
KC 1092-A	2.925	3-7/8	17.70	2600	11	1600	4:1	7810	1.500
Program Runs									
KC 1108-A	2.925	4-1/4	19.48	3400	9	1600	4:1	7810	1.499
KC 1108-B	2.925	4-1/4	19.26	3400	9	1600	4:1	7810	1.523
KC 1104-A	2.925	4-1/4	19.61	3100	11	1700	4:1	7052	1.511
KC 1092-B	2.925	3-7/8	17.95	3100	8	1700	4:1	7052	1.509
KC 1105-A	2.925	4-1/4	19.50	2800	11	1800	4:1	7052	1.505
KC 1105-B	2.925	4-1/4	19.43	2800	8	1800	4:1	7052	1.493

Lubrication

Die & container: (in all billets) — Aquadag. Trade name for Colloidal graphite in water manufactured by Acheson.

Die condition: (in all billets) — Reconditioned.

(1) The thermocouple became defective during the heating cycle. This temperature is an estimate based on the power requirements.

(2) This number refers to a grade of 100 mesh glass manufactured by Corning Glass.

(3) The die was plasma coated with an underlayer of nickel-chromium from 2 to 5 mils in the diameter and zirconium oxide from 20 to 25 mils in the diameter.

TABLE 6

EXTRUSION PARAMETERS USED FOR HIGH SPEED PRESS EXTRUDING THE W-.6Cb ALLOY

Billet Number	BILLET Diameter (Inches)	BILLET Length (Inches)	Weight (lbs.)	Temp. (°F.)	Transfer Time (Sec.)	Ext. Ratio	LUBRICATION Billet	DIE Bore (Inches)
Program Runs								
KC 1109-B	3	4-1/4	20.20	2800	9	4:1	7052(2)	1.550
KC 1110-A	3	4-3/16	20.20	2800	10	4:1	7052	1.538
KC 1110-B	3	4-1/4	20.34	3100	9	4:1	7052	1.546
KC 1111-A	3	4-1/4	20.44	3100	11	4:1	7052	1.546
KC 1111-B	3	4-1/4	20.54	3400	8	4:1	7052	1.572(3)
KC 1086-A	3	4	19.41	3400	11	4:1	7810	1.541
KC 1086-B	3	3-15/16	18.85	3400	20(1)	4:1	7810	1.558

Lubrication

Die (in all billets): Graphite & grease. Fiske's lubricant No. 604 manufactured by Fiske Brothers Refining Co.

Container (in all billets): Same as in the die.

Die condition (in all billets): Reconditioned.

(1) This billet was dropped.

(2) This number refers to a grade of 100 mesh glass manufactured by Corning Glass.

(3) This die was plasma coated with an underlayer of molybdenum from 2 to 5 mils and a mixture of zirconium oxide plus aluminum oxide from 20 to 25 mils in the diameter.

TABLE 7

DIMENSIONS, VOLUMES, K VALUES, AND ENERGY VALUES OF DYNAPAK EXTRUDED MOLYBDENUM ALLOY BARS

Billet Number	Fire Pressure (psi)	Temp. °F.	EXTRUDED BAR Diameter Nose	Center	Tail	Length	Energy Ft.-Lb.
Base Information							
8067-3	1500	2915	1.485"	1.494"	1.492"	9-1/4"	300,000
8067-4	1500	2840	1.493"	------	1.488"	5-1/2"	280,000
8070-3	1500	3450	1.486"	1.482"	1.487"	7-1/8"	290,000
8070-4	1500	3460	1.492"	1.485"	1.486"	7-5/8"	290,000
8070-6	1800	2700	1.495"	1.495"	1.500"	7-1/2"	350,000
8069-4	1800	2985	1.495"	1.493"	1.495"	7-1/16"	330,000
Program Runs							
8069-3	1800	3495	1.521"	1.522"	1.537"	10-3/16"	350,000
8071-5	1800	2955	1.502"	1.502"	1.504"	5-13/16"	330,000
8071-6	1800	2705	1.510"	1.508"	1.514"	4-5/16"	320,000
8072-3	1800	2950	1.517"	1.515"	1.524"	6-5/16"	33C,000
8072-4	1800	3500	1.490"	1.488"	1.495"	10-1/2"	350,000
8072-5	2000	2700	1.524"	1.523"	1.531	7-1/16"	370,000

TABLE 7 (continued)

DIMENSIONS, VOLUMES, K VALUES, AND ENERGY VALUES OF DYNAPAK EXTRUDED MOLYBDENUM ALLOY BARS

Billet Number	Fire Pressure (psi)	Temp. °F.	Volume $In.^3$	Net Stroke	Energy Ft.-Lb.	Volume per 1000 Ft.-Lb. $In.^3$	K Value (psi)
Base Information							
8067-3	1500	2915	16.123	11-15/16"	300,000	.0537	146,957
8067-4	1500	2840	9.620	11-5/16"	280,000	.0344	119,269
8070-3	1500	3450	12.348	11-5/8"	290,000	.0426	162,352
8070-4	1500	3460	13.287	11-3/4"	290,000	.0458	157,842
8070-6	1800	2700	13.185	11-3/4"	350,000	.0377	185,351
8069-4	1800	2985	12.374	11"	330,000	.0375	174,759
Program Runs							
8069-3	1800	3495	19.001	11-13/16"	350,000	.0543	139,959
8071-5	1800	2955	10.320	10-9/16"	330,000	.0313	202,065
8071-6	1800	2705	7.746	10-1/8"	320,000	.0242	236,546
8072-3	1800	2950	11.458	10-3/4"	330,000	.0347	191,999
8072-4	1800	3500	18.365	11-11/16"	350,000	.0525	137,159
8072-5	2000	2700	12.198	11-1/8"	370,000	.0330	338,229

TABLE 8

DIMENSIONS, FORCES AND K VALUES FOR HIGH SPEED PRESS EXTRUDED MOLYBDENUM ALLOY BARS

Billet Number	Ext. Temp. °F	Peak Force (Tons)	K Value (psi)	Extruded Bar: Diameter: Nose	Extruded Bar: Diameter: Center	Extruded Bar: Diameter: Tail	Extruded Bar: Length	Depth of Pipe	Useable Length (3)
Base Information									
8068-3	2670			1.560"	1.599"	1.638"	11-7/8"	4-1/8"	7-7/16"
Program Runs									
8074-4	3500	345	64,864	1.560"	1.629"	1.750"	16-5/8"	2-1/8"	14-3/16"
8074-3	3500	327	61,553	1.564"	1.613"	1.704"	16-1/8"	1-5/8"	14-3/16"
8074-5	2950	405(1)	76,182	1.557"	1.655"	1.717"	16-1/4"	2-1/4"	13-11/16"
8073-1	2950	442	83,162	1.568"	1.640"	1.722"	15-1/8"	3"	11-13/16"
8073-4	2700	---(2)	------	1.560"	1.620"	1.689"	15"	3-3/4"	10-15/16"
8073-5	2700	469	97,688	1.660"	1.729"	1.779"	12-1/2"	2-1/2"	9-11/16"

(1) Estimated value.
(2) No recording values were obtained during this run.
(3) Assuming we cut a 5/16" length from the nose of the extrusion.

TABLE 9

EXTRUSION DIE BORE DIAMETER BEFORE AND AFTER EXTRUDING THE MOLYBDENUM ALLOY BAR

Press Extrusions				Dynapak Extrusions		
Billet Number	Before	After	Extrusion Temp. ^{o}F	Billet Number	Before	After
			Base Information Extrusions			
			2915	8067-3	1.500	1.529
			2840	8067-4	1.500	1.527
			3450	8070-3	1.500	1.506
			3460	8070-4	1.500	1.529
			2700	8070-6	1.500	1.517
			2985	8069-4	1.500	1.526
			Program Extrusions			
8074-4	1.562	1.715	3500	8069-3	1.529	1.624
8074-3	1.562	1.718	3500	8072-4	1.500	1.511
8074-5	1.562	1.732	2950	8071-5	1.506	1.507
8073-1	1.562	1.731	2950	8072-3	1.526	1.527
8073-4	1.562	1.708	2700	8072-5	1.529	1.532
8073-5	1.562	1.795	2700	8071-6	1.517	1.518

TABLE 10

CHEMISTRY AND HARDNESS OF DYNAPAK EXTRUDED MOLYBDENUM ALLOY BARS

		CHEMICAL ANALYSIS				HARDNESS					
		O_2 ppm		N_2 ppm		Trans. DPH(1)			Longitudinal - DPH		
Billet Number	Extrusion Temp., °F	Nose	Tail	Nose	Tail	Edge	Cent.	Edge	Edge	Mid-Rad.	Cent.
8071-6	2705	6	6	2.5	2	269	254	261	292	292	270
8072-5	2700	6	5.5	2.5	2	284	254	298	327	311	278
8071-5	2955	7	2	2.5	1.5	226	226	226	258	258	250
8072-3	2950	7	5	2	2	214	208	232	278	270	278
8069-3	3495	4	8	2	2	198	203	193	258	258	258
8072-4	3500	4	8	2	3.5	176	188	193	243	250	243

(1) These readings were converted from Rockwell Hardness number, scale B by using the Steel Hardness Conversion Tables. Each number is the average of two readings.

TABLE 11

CHEMISTRY AND HARDNESS OF HIGH SPEED PRESS EXTRUDED MOLYBDENUM ALLOY BARS

		CHEMICAL ANALYSIS				HARDNESS					
		O_2 ppm		N_2 ppm		Trans., DPH (1)			Longitudinal - DPH		
Billet Number	Extrusion Temp., °F	Nose	Tail	Nose	Tail	Edge	Cent.	Edge	Edge	Mid-Rad.	Cent.
8073-4	2700	3.5	5	1.5	2	269	254	276	292	292	270
8073-5	2700	2.5	2.5	1	1	261	254	261	292	278	270
8074-5	2950	3	5.5	1	2	254	226	240	258	250	250
8073-1	2950	3	3	1	1	240	220	240	270	278	270
8074-4	3500	5	3	1	1	220	203	240	258	250	243
8074-3	3500	4	2.5	2	1	226	203	220	258	250	250
8073-3	As Cast	-	-	-	-	-	-	-	-	-	-

(1) These readings were converted from Rockwell Number, scale B by using the Steel Hardness Conversion Tables. Each number is the average of two readings.

TABLE 12

TENSILE PROPERTIES OF DYNAPAK EXTRUDED MOLYBDENUM ALLOY BARS

			AS-EXTRUDED				AS-ANNEALED: 3000°F, 1 HR.			
Billet Number	Ext. Temp., °F	Test Temp., °F	Ult. Str. psi	Yield Str. (.2%) psi	Elong. %	R.A. %	Ult. Str. psi	Yield Str. (.2%) psi	Elong. %	R.A. %
8071-6	2700	R.T.		No Test				No Test		
		2000	58,600	47,500	19.3	86.0*	45,500	27,100	34	91.4
8072-5	2700	R.T.	57,000	*	*	*	62,000	*	.6	.6
		2000		No Test				No Test		
8071-5	2950	R.T.	78,000	*	*	*	78,000	----	1.6	1.6
		2000		No Test				No Test		
8072-3	2950	R.T.		No Test				No Test		
		2000	52,700	32,500	28.0	85	51,600	35,000	28.7	90.2
8069-3	3500	R.T.	57,000	*	*	*	73,000	67,000	6.7	6.2
		2000	44,200	24,800	32.0	88	45,900	22,700	32.0	88.8
8072-4	3500	R.T.	57,000	*	*	*	79,000	66,000	4.6	4.9
		2000	42,200	21,200	31.3	85		No Test		

*All the specimens broke in the threads and the values reported represent only the breaking strength.

TABLE 13

TENSILE PROPERTIES OF HIGH SPEED PRESS EXTRUDED MOLYBDENUM ALLOY BARS

Billet Number	Ext. Temp., °F	Test Temp., °F	AS EXTRUDED Ult. Str. psi	AS EXTRUDED Yield Str. (.2%) psi	AS EXTRUDED Elong. %	AS EXTRUDED R.A. %	AS-ANNEALED: 3000°F, 1 HR. Ult. Str. psi	AS-ANNEALED: 3000°F, 1 HR. Yield Str. (.2%) psi	AS-ANNEALED: 3000°F, 1 HR. Elong. %	AS-ANNEALED: 3000°F, 1 HR. R.A. %
8074-4	3500	R.T.	63,000*	*	.0	.0	92,000	79,000	12	10
		2000	45,100	30,500	29.3	78.1		No Test		
8074-3	3500	R.T.	64,100*	*	.0	.1	79,000	76,000	3.3	3.9
		2000	44,300	27,800	34.0	74.6	42,700	22,500	36.0	89.4
8074-5	2950	R.T.	59,800*	*	.0	.0	80,500	*	16	-
		2000	51,200	40,600	29.3	84.8		No Test		
8073-1	2950	R.T.	81,000*	*	.0	.0	86,000	80,000	1.9	3
		2000	50,800	39,500	28.0	76.0	43,000	23,000	36.0	90.9
8073-4	2700	R.T.	92,100*	*	1.4	1.3	95,000	76,000	10.6	9
		2000	56,100	34,400	27.3	84.0	49,100	40,000	28.0	90.0
8073-5	2700	R.T.	82,500*	*	.7	.2	77,000	-	.6	-
		200	54,100	46,800	22.6	75.7		No Test		
8073-3	As-Cast	R.T.	49,000	49,000	.7	1.5		No Test		
		2000	31,800	18,800	24.6	65.3		No Test		

* All specimens, except the as-cast specimen broke in the threads and represent only the breaking strength.

TABLE 14

DIMENSIONS, VOLUMES, K VALUES AND ENERGY VALUES OF DYNAPAK EXTRUDED TUNGSTEN ALLOY BARS

			EXTRUDED BAR				
			Diameter				
Billet Number	Fire Pressure (psi)	Temp. °F	Nose	Center	Tail	Length	Energy Ft. Lb.
Base Information							
1084	1500	3900 (1)	1.482"	1.481"	1.487"	12-3/4"	237,500
1085-A	1500	3440	1.483"	1.483"	1.4825"	9-15/16"	230,000
1085-B	1625	3200	1.488"	1.488"	1.489"	9-1/2"	248,500
1091-A	1600	3000	1.488"	1.484"	1.485"	7-1/2"	223,750
1091-B	1600	2800	1.495"	1.496"	1.500"	6-1/2"	220,000
1092-A	1600	2600	1.530"	1.530"	1.545"	6"	------- (2)
Program Runs							
1108-A	1600	3400	1.493"	1.492"	1.490"	7-5/8"	222,500
1108-B	1600	3400	1.517"	1.519"	1.519"	8-3/8"	225,000
1104-A	1700	3100	1.560"	1.550"	1.549"	5"	230,000
1092-B	1700	3100	1.513"	1.512"	1.512"	8-3/8"	245,000
1105-A	1800	2800	1.512"	1.521"	1.523"	7-1/2"	255,000
1105-B	1800	2800	1.497"	1.495"	1.496"	8"	259,000

(1) The thermocouple became defective during the heating cycle. This temperature is an estimate based on the power requirements.

(2) Butt shattered during extrusion. No measure was made.

TABLE 14 (continued)

DIMENSIONS, VOLUMES, K VALUES AND ENERGY VALUES OF DYNAPAK EXTRUDED TUNGSTEN ALLOY BARS

Billet Number	Fire Pressure (psi)	Temp. °F	Volume Cu. In.	Net Stroke	K Value (psi)	Energy Ft. Lb.	Volume Cu. In. Per 1000 Ft. Lb.
Base Information							
1084	1500	3900(1)	22.032	11-3/8"	83,100	237,500	.0928
1085-A	1500	3440	17.161	11"	128,762	230,000	.0746
1085-B	1625	3200	16.527	10-3/16"	115,932	248,500	.0665
1091-A	1600	3000	13.001	10-7/16"	118,492	223,750	.0581
1901-B	1600	2800	11.001	10-1/8"	186,747	220,000	.0500
1092-A	1600	2600	11.103	------(2)	------	--------	------
Program Runs							
1108-A	1600	3400	13.324	9-3/4"	117,830	222,500	.0589
1108-B	1600	3400	15.161	10-1/16"	104,969	225,000	.0674
1104-A	1700	3100	9.471	9-3/16"	160,952	230,000	.0412
1092-B	1700	3100	15.042	10-3/16"	126,460	245,000	.0613
1105-A	1800	2800	13.584	9-3/4"	135,041	255,000	.0532
1105-B	1800	2800	14.062	9-15/16"	126,995	259,000	.0542

(1) The thermocouple became defective during the heating cycle. This temperature is an estimate based on the power requirements.

(2) Butt shattered during extrusion. No measure was made.

TABLE 15

DIMENSIONS, FORCES AND K VALUES FOR HIGH SPEED PRESS EXTRUDED TUNGSTEN ALLOY BARS

Billet Number	Temp. (°F.)	Peak Force (Tons)	K (psi)	EXTRUDED BAR Diameter Nose	Center	Tail	Length (Inches)	Depth of Pipe (In.)	Useable(1) Length (In.)
Program Runs									
1086-A	3400	369	69,450	1.545"	1.547"	1.546"	16-1/4	2	13-15/16
1086-B	3400	485	91,262	1.558"	1.557"	1.555"	15-1/2	2-1/4	12-15/16
1109-B	2800	541	101,735	1.575"	1.576"	1.580"	16-3/8	8	8-1/16
1110-A	2800	448	84,223	1.555"	1.551"	1.554"	16	2-7/8	12-13/16
1110-B	3100	444	83,530	1.535"	1.535"	1.540"	17-5/8	2-1/4	15-1/16
1111-A	3100	378	71,190	1.547"	1.546"	1.547"	17-1/4	2-5/8	14-5/16
1111-B	3400	415	77,991	1.571"	1.578"	1.585"	16-1/2	3-1/16	13-2/16

(1) Assuming we cut a 5/16" length from the nose of the extruded specimen.

TABLE 16

EXTRUSION DIE BORE DIAMETER BEFORE AND AFTER EXTRUDING THE TUNGSTEN ALLOY BARS

Press Extrusions

Billet Number	Before	After	Extrusion Temp. °F
1086-A	1.541	1.556	3400
1086-B	1.558	1.555	3400
1111-B	1.572	1.591	3400
1111-A	1.546	1.551	3100
1110-B	1.546	1.544	3100
1110-A	1.538	----- (1)	2800
1109-B	1.550	----- (1)	2800

(1) The coating of the die was badly damaged in this process. No measures were obtained. The coating on all the Dynapak dies was too badly damaged to obtain a significant reading.

TABLE 17

CHEMISTRY AND HARDNESS OF DYNAPAK EXTRUDED TUNGSTEN ALLOY BARS

Billet Number	Ext. Temp., °F	CHEMICAL ANALYSIS O_2 ppm Nose	O_2 ppm Tail	N_2 ppm Nose	N_2 ppm Tail	HARDNESS Transverse DPH (1) Nose Center	Nose Edge	Center (2) Center	Center (2) Edge	Tail Center	Tail Edge	Longitudinal DPH Center	Longitudinal DPH Edge
1108-A	3400	3	4	1	1	405	405			405	366	365	372
1108-B	3400	3	10	1	2	424	405			384	366	403	365
1104-A	3100	4	5	1	1	405	405			424	424	423	412
1092-B	3100	4	5	1	1	384	366			424	348	383	402
1105-A	2800	4	4	1	1	444	444			348	384	470	457
1105-B	2800	6	5	1	1	424	405			491	444	485	479

(1) These readings were converted from Rockwell A readings by using the Steel Hardness Conversion Tables.

(2) No readings were taken at this part. Dynapak extrusions were too short to obtain hardness readings at the center.

TABLE 18

CHEMISTRY AND HARDNESS OF HIGH SPEED PRESS EXTRUDED TUNGSTEN ALLOY BARS

Billet Number	Ext. Temp., °F	CHEMICAL ANALYSIS O_2 ppm Nose	CHEMICAL ANALYSIS O_2 ppm Tail	N_2 ppm Nose	N_2 ppm Tail	HARDNESS Transverse DPH (1) Nose Center	Nose Edge	Center Center	Center Edge	Tail Center	Tail Edge	Longitudinal DPH Center	Longitudinal DPH Edge
1086-A	3400	3	3	1	1	349	405	55*	269	349	367	439	401
1086-B	3400	3	3	1	1	367	349	403	367	349	367	482	482
1110-B	3100	5	4	1	1	330	384	55*	59*	349	367	467	498
1111-A	3100	4	4	1	1	53*	59*	229**	269	330	330	482	482
1109-B	2800	5	4	1	1	403	367	403	403	425	425	498	482
1110-A	2800	6	3	1	1	330	349	283	330	330	425	482	482
1111-B	3400	9	3	1	1	367	384	269	349	444	425	467	467

(1) These readings were converted from Rockwell Hardness number, Scale A. They are averaged values from two readings. The Hardness values were converted by using the Steel Hardness Conversion Tables.

* These values are R_A readings. They are averaged values from two readings. No conversion relationship between R_A and DPH scale was available for any value lower than 60.7 in R_A scale.

** Extrapolated value from Conversion Table.

TABLE 19

TENSILE PROPERTIES OF DYNAPAK EXTRUDED TUNGSTEN ALLOY BARS

			AS-EXTRUDED				AS-ANNEALED: 3000°F, 1 HR.			
Billet Number	Ext. Temp. °F	Test Temp. °F	Ult. Str. psi	Yield Str. (.2%) psi	Elong. %	R.A. %	Ult. Str. psi	Yield Str. (.2%) psi	Elong. %	R.A. %
1108-A-C	3400	R.T.	44,400[1]	---	0	0		No Test		
		3000	29,100	16,700	29.5	31.0		No Test		
1108-B-C	3400	R.T.			No Test		47,700	---	0	0
		3000			No Test		24,800	13,200	42.5	82.4
1092-B-C	3100	R.T.	59,900	---	0	0		No Test		
		3000			No Test			No Test		
1104-A-C	3100	R.T.			No Test		50,050	---	0	0
		3000			No Test		36,100	19,000	33.5	88.0
1105-A-C	2800	R.T.	182,600	---	0	0		No Test		
		3000	43,500	40,000	12.0	80.7		No Test		
1105-B-C	2800	R.T.			No Test		34,700	---	0	0
		3000			No Test		24,100	12,800	46.1	92.5

(1) This value is also the breaking strength.

TABLE 20

TENSILE PROPERTIES OF HIGH SPEED PRESS EXTRUDED TUNGSTEN ALLOY BARS

Billet Number	Ext. Temp., °F	Test Temp., °F	AS-EXTRUDED Ult. Str. psi	AS-EXTRUDED Yield Str. (.2%) psi	AS-EXTRUDED Elong. %	AS-EXTRUDED R.A. %	AS-ANNEALED: 3000°F, 1 HR. Ult. Str. psi	AS-ANNEALED: 3000°F, 1 HR. Yield Str. (.2%) psi	AS-ANNEALED: 3000°F, 1 HR. Elong. %	AS-ANNEALED: 3000°F, 1 HR. R.A. %
1086-A-C	3400	R.T.	49,000*	**	0	0	34,900*		0	0
		3000		No Test				No Test		
1086-A-F	3400	R.T.		No Test				No Test		
		3000	24,600	19,300	28.4	83.9	22,000	10,500	49.8	75.0
1086-B-C	3400	R.T.	21,750		0	0	28,400		0	0
		3000		No Test				No Test		
1086-B-F	3400	R.T.		No Test				No Test		
		3000	36,300	35,200	7.5	53.3	22,900	13,600	43.6	84.3
1111-B-C	3400	R.T.	153,730		0	0	38,700		0	0
		3000		No Test				No Test		
1111-B-F	3400	R.T.		No Test				No Test		
		3000	35,700	35,100	16.5	77.4	28,100	19,900	34.3	83.7
1110-B-C	3100	R.T.	181,000		0	0	39,600		0	0
		3000		No Test				No Test		
1110-B-F	3100	R.T.		No Test				No Test		
		3000	41,800	40,600	16.0	81.0	27,600	19,000	20.6	84.9
1111-A-C	3100	R.T.	150,000***		0	0		No Test		
		3000		No Test				No Test		
1111-A-F	3100	R.T.		No Test				No Test		
		3000	35,600	33,400	15.0	82.4	24,750	17,400	29.8	89.4
1109-B-C	2800	R.T.	183,200		0	0	27,700		0	0
		3000		No Test				No Test		
1109-B-F	2800	R.T.		No Test				No Test		
		3000	51,600	47,000	12.5	69.0	31,850	20,100	32.1	80.6
1110-A-C	2800	R.T.	131,700		0	0	29,500		0	0
		3000		No Test				No Test		
1110-A-F	2800	R.T.		No Test				No Test		
		3000	45,800	42,400	14.0	85.1	28,800	22,600	26.8	76.2

* This value is also the breaking strength.
** No yield strength was observed.
*** A second sample of this extrusion was tensile tested. This result was only 33,000 psi.

TABLE 21

APPROXIMATE AMOUNTS OF RECRYSTALLIZATION AND AVERAGE GRAIN SIZE IN THE AS-EXTRUDED CONDITION FOR HIGH SPEED PRESS AND DYNAPAK EXTRUDED TUNGSTEN ALLOY BARS

High Speed Press

Billet Number	Ext. Temp., °F		NOSE Center	NOSE Mid Rad	NOSE Edge	CENTER Center	CENTER Mid Rad	CENTER Edge	TAIL Center	TAIL Mid Rad	TAIL Edge
1086-A	3400	Recryst. %	90	90	95	90	90	95	35	35	85
		Grain Size	6/7	7/8	7/8	6/7	6/7	7/8	7/8	7/8	7/8
1086-B	3400	Recryst. %	W	W	W	W	W	W	W	W	W
		Grain Size	--	--	--	--	--	--	--	--	--
1111-B	3400	Recryst. %	Tr	Tr	W	10	10	Tr	10	Tr	Tr
		Grain Size	--	--	--	7/8	8	--	8	--	--
1110-B	3100	Recryst. %	W	W	W	Tr	W	W	W	W	W
		Grain Size	--	--	--	--	--	--	--	--	--
1111-A	3100	Recryst. %	W	W	W	10	10	W	Tr	Tr	Tr
		Grain Size	--	--	--	8	8	--	--	--	--
1109-B	2800	Recryst. %	W	W	W	W	W	W	W	W	W
		Grain Size	--	--	--	--	--	--	--	--	--
1110-A	2800	Recryst. %	W	W	W	W	W	W	W	W	W
		Grain Size	--	--	--	--	--	--	--	--	--

W - Wrought

Tr - Trace of recrystallization

TABLE 21 (continued)

APPROXIMATE AMOUNTS OF RECRYSTALLIZATION AND AVERAGE GRAIN SIZE IN THE AS-EXTRUDED CONDITION FOR HIGH SPEED PRESS AND DYNAPAK EXTRUDED TUNGSTEN ALLOY BARS

Dynapak

			NOSE			CENTER			TAIL		
Billet Number	Ext. Temp., °F		Center	Mid Rad	Edge	Center	Mid Rad	Edge	Center	Mid Rad	Edge
1108-A	3400	Recryst. %	95	85	80				100	97	95
		Grain Size	5/6	6/7	6/7				6/7	6/7	7/8
1108-B	3400	Recryst. %	95	85	75				97	95	95
		Grain Size	5/6	6/7	6/7				6/7	6/7	7/8
1092-B	3100	Recryst. %	50	30	20				60	40	30
		Grain Size	6/7	7/8	7/8				6/7	7/8	7/8
1104-A	3100	Recryst. %	40	20	10				40	20	15
		Grain Size	7/8	7/8	7/8				---	7/8	7/8
1105-A	2800	Recryst. %	10	Tr	W				15	Tr	W
		Grain Size	---	---	---				---	---	---
1105-B	2800	Recryst. %	15	Tr	W				10	Tr	W
		Grain Size	---	---	---				---	---	---

Aeronautical Systems Division, Dir/Materials & Processes, Metals & Ceramics Lab, Wright-Patterson AFB, Ohio.
Rpt Nr ASD-TDR-62-506. COMPARISON OF HIGH ENERGY RATE (DYNAPAK) AND CONVENTIONAL EXTRUSION OF REFRACTORY METALS. Final report, **Sept 62, 90p. incl illus., tables, & 6 refs.**
Unclassified Report

A comparison was made of the surface quality dimensions, chemistry, hardness, tensile properties, and recrystallization behavior of extrusions produced by high-velocity and conventional techniques. Temperatures were established for the development of hot-worked, cold-worked, and duplex metallurgical structures for the Mo-25W-0.1Zr and W-0.6Cb

(over)

alloys which were then extruded by both methods at a constant 4:1 reduction ratio. The data indicate that equally good surface conditions can be obtained from the two processes if proper lubrication and tooling are used; lower hot working temperatures can be used for high-velocity extrusions; and lower recrystallization temperatures are obtained in material cold worked on a high-velocity machine. The latter fact indicates that high-velocity-extruded metals retain a higher degree of internal stress than do conventional-extruded metals.

1. Extrusion of Refractory Metals
2. Molybdenum Alloys
3. Extrusion of Molybdenum & Tungsten Alloys
4. Tungsten Alloys

I. AFSC Project 7381, Task 73811
II. Contract Nr AF 33(616)-7842
III. Westinghouse Elec Corp., Pittsburgh, Penn.
IV. Rabenold, Dirk G.
V. Aval fr OTS
VI. In ASTIA collection

Aeronautical Systems Division, Dir/Materials & Processes, Metals & Ceramics Lab, Wright-Patterson AFB, Ohio.
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